A COMPARATIVE ANALYSIS OF WELDED Al-6061 SHEET JOINED BY MIG AND TIG WELDING METHODS

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By

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ABSTRACT

The present work deals with the assessment of tensile strength, hardness, and microstructural changes in welded Al 6061 plates. Based on that, the performance of two different welding techniques- metal inert gas welding (MIGW) and tungsten inert gas welding (TIGW) has been compared. All the sheets were having a thickness of 3.0 mm. MIG welding has been done with a filler wire also same filler metal has been applied during TIG welding for comparing the results. Tensile samples were prepared as per ASTM-E8/E8M-09 Standard from the MIG welded specimens. Tensile test was made using Universal Testing Machine (UTM) with hydraulic grip. The microstructure of all the specimens were carried out using Metallurgical microscope with Image Analyzer System, the Microhardness study was carried out using Digital Vickers Microhardness tester. The primary phase (bright Al-grains) of the base metal zone (BM) with thin solid boundary has changed into thick dendritic shapes in the welded zone (WZ). Also, the coarse secondary phase of BM has converted into fine particles in WZ under the influence of rapid cooling. The WZ has been reported harder than HAZ in MIG and TIGW Sheet has been found harder than WZ due to the accumulation of fine equiaxed secondary phase.

Keywords: Al-6061; MIGW; TIGW; Tensile strength; Hardness; Microstructure

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CHAPTER- 1

INTRODUCTION

1.1 BACKGROUND

Aluminium (Al) is a soft, highly ductile, and less-hard material due to its FCC lattice structure. Its strength is comparatively less than other materials like hardened steel, carbides, and ceramics etc. Al is a highly corrosion resistant metal due to the formation of a thin transparent oxide film on the newly polished surface which acts as a protective layer against atmospheric corrosion. Some of its uses include aerospace and automotive products, structural products for construction as well as marine applications. Aluminium alloys are often welded, and the quality of the welds has a direct impact on performance and service life of parts and products. The main applications of aluminium products have been in transportation (27%), construction (20%), packaging (16%), electricity supply (10%), machinery and equipment (8%) and in sectors relating to sustainable products (7%) where extraordinary growth reaching 60 million tons by 2020 has been predicted. Among all, Al- 6160 is the most widely used alloy for different general purposes works and kitchen utensils. Mg, Fe, Si are the main alloying elements in 6160. In automobile industry most of the applications are sheet based; and these are conventionally joined by riveting. Major Disadvantages of riveting are extra weight to the structure, stress concentration, crevices corrosion and loosening due to vibrations. Moreover, it is a time consuming and manpower intense task. Thus, conventional welding took the place of riveting which in-turn decreases the weight of the vehicles and increases their fuel efficiency; and more over reduces the CO2 emission [1-4]. During welding of aluminium alloys, it must overcome some challenges due to its physical properties such as tenacious oxide layer, high thermal conductivity, high coefficient of thermal expansion, solidification shrinkage and above all high solubility of hydrogen gases in molten state. Apart from these, liquation cracking and softening or property degradation in the heat affected zone and partially melted zone [5-6] are the other problems. Softening is one of the major concerns of 6xxx alloy [6-11] and besides softening behaviour in the weld fusion zone and heat affected zones, hot cracking is also an issue.

Conventional processes like gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) are preferred for joining aluminium alloys. During conventional arc process the heat of welding can results in melting of low melting phases which leads to hot cracking in the fusion zone (FZ) and heat affected zone (HAZ) [12, 13]. Arc welding process deteriorates the mechanical properties of the welded joint due to its high heat input nature [14].

Aluminium is difficult to weld metal by any of the arc welding techniques. Due to its low melting temperature, a less heat input is required at the fusion zone. TIG and MIG welding methods may be applied to weld aluminium plates. TIG provides a clean welding due to less heat input and thereby no splashing of molten metal. The application of filler metal was analysed on the welding process of 6061 Al alloy. The joint was made by TIG welding. The filler ER-4043 showed higher hardness than ER-4047 [6]. The mechanical characteristics and microstructural attributes of the joint were analysed. The weldment hardness was found higher in 6061 alloy. The tensile strength of the similar joint was reported higher than that of the dissimilar joint. The intermetallic formation in the welded zone was responsible for the high strength of the joint [8]. Two primary approaches of welding are Tungsten Inert Gas (TIG) welding and Metal Inert Gas (MIG) welding, which is regularly applied to connect aluminium 6061. TIG and MIG welding techniques both have their advantages and disadvantages when welding Al 6061 and the choice between the two is determined by the quality of weld required, the thickness of material being welded, production volume, and specific application. To promote weldability enhancement, it is crucial to comprehend the relative merits and demerits of these welding methodologies for welding processes and the performance fascination in the fabricated parts. However, there is the lack of the detailed comparative investigation of TIG and MIG welding for aluminium alloys in terms of the mechanical properties of the welds, their microstructure, and overall quality. Such a study will be of immense value towards identifying the most appropriate welding procedure to use for welding aluminium 6061 for use in industrial applications by designers and manufacturers.

This research seeks to address this shortfall by offering a comprehensive comparative evaluation of aluminium 6061 welded using the TIG and MIG approaches. This study on aluminium 6061 aims at establishing the effects of the above welding methods on the mechanical properties, and microstructure and weld quality of aluminium 6061. These findings will extend the understanding of welding technology and provide useful information for welding application in industries. Comparing TIG and MIG welding when working with aluminium 6061 depends on numerous issues, for instance, area of application, material thickness, desired weld quality, and manufacturing rate. It is therefore important to understand the strengths and limitations of these welding methods to be able to make the right decisions especially in industrial applications. The main purpose of this thesis is to compare welded joints of aluminium 6061 using TIG and MIG methods. Therefore, this study aims at offering important information for the best welding practices of aluminium 6061 through the analysis of the mechanical properties, microstructure, and overall weld quality generated by each of the methods.

1.2 AIM OF STUDY

Two prevalent welding techniques for aluminium 6061 are Tungsten Inert Gas (TIG) welding and Metal Inert Gas (MIG) welding. TIG welding is renowned for producing high-quality welds with precise control, but it is often slower and requires more skill. In contrast, MIG welding is faster and easier to automate, making it suitable for large-scale production, but it may result in lower weld quality if not properly managed. Despite the extensive use of these welding methods, there is a lack of comprehensive comparative studies that systematically evaluate the performance of TIG and MIG welding for aluminium 6061. Understanding the strengths and weaknesses of each welding process is crucial for optimizing welding practices, improving production efficiency, and ensuring the integrity and reliability of welded structures. This study aims to fill this gap by conducting a detailed comparative analysis of TIG and MIG welding processes on aluminium 6061. By examining various aspects such as weld quality, mechanical properties, microstructural characteristics, and overall performance, this research seeks to provide valuable insights that will aid in selecting the most suitable welding technique for specific applications. The findings of this study will not only contribute to the academic understanding of welding processes but also have practical implications for industries relying on aluminium 6061 components. By comparing TIG and MIG welding, this study endeavours to identify the optimal welding process that balances quality, efficiency, and cost-effectiveness, ultimately contributing to the development of better-engineered products.

1.3 LIMITATION

Despite the comprehensive approach taken in this thesis, several limitations exist that may impact the generalizability and applicability of the findings. These limitations are outlined below:

- Welding Parameters: The welding parameters (e.g., current, voltage, travel speed, and shielding gas flow rate) used in this study were selected based on standard practices and recommendations for aluminium 6061. Variations in these parameters could influence the weld quality and mechanical properties, and different settings might yield different results.
- Operator Skill: The skill level and experience of the welding operators can significantly impact the quality of the welds. While efforts were made to standardize

the welding process, variations in operator technique and proficiency could influence the outcomes.

- Economic Considerations: While the technical performance of TIG and MIG welds was evaluated, the economic aspects (e.g., cost of materials, labour, and equipment) were not considered in detail. These factors are crucial for practical decision-making in industrial applications.

1.4 OUTLINE OF THE THESIS

The thesis comprises of five chapters. Significance of the problem taken up is discussed in Chapter-1, Introduction. Literature Review section presents findings from previous studies on aluminium 6061 and welding processes of TIG and MIG. This chapter provides the existing research gap and situates the study in context of the welding technology literature in Chapter 2. Chapter 3 presents the materials and equipment that were used in the experiments, the welding techniques used, and the conditions set for both TIG and MIG welding. Chapter 4 contains the findings of the experiments done on the welded joints by way of visually inspect, tensile strength, hardness test, and microstructure analysis. This chapter aims at comparing the weld quality resulting from TIG and MIG welding. Details of all the references cited throughout the thesis are compiled at the end in reference section.

CHAPTER 2:

LITERATURE REVIEW

2.1 OVERVIEW OF ALUMINIUM ALLOYS

Aluminium alloys are categorized under most common non-ferrous alloys, one of the heavily consumed metals in the world right after the steel due to its attractive combination of physical and mechanical properties [18]. Several aluminium alloys have been developed to cater the needs of different industrial and engineering applications like automobile, aviation, marine, and enormous varieties of other products that we come across in everyday living [19]. Due to the modern environmental policy and fuel scarcity every automobile industry is looking forward to decreasing the weight of the vehicles which would decrease the fuel consumption and in turn increase the efficiency of the motor vehicles [20]. In case of aerospace applications, after costly Titanium alloys, Al alloys are the only possibilities when metallic structure is needed. A unique combination of properties (light weight, high-strength to-weight ratio, good corrosion resistance, excellent thermal and electrical conductivities, non-magnetic character, suitability for low temperature applications because of its FCC crystal structure) makes aluminium and its alloys one of the most versatile and economically attractive metallic material for a broad range of uses, from soft, highly ductile wrapping foil to the most demanding engineering applications [21]. Pure aluminium can be readily alloyed with many other metals to produce a wide range of physical and mechanical properties, and this required to increase the strength of soft aluminium. There are a variety of aluminium alloys which are in commercial use today and those can be classified into: 1xxx (commercially pure aluminium), 2xxx (Al-Cu alloys), 3xxx (Al-Mn alloys) 4xxx (Al-Si alloys), (5xxx Al-Mg alloys) 6xxx (Al-Mg-Si alloys), and 7xxx (Al-Zn-Mg) series. Among these, 2xxx, 6xxx, 7xxx are precipitation hardenable and can be processed to high strength levels. Wrought aluminium alloys are generally designated by using a four-digit numbering system, originally proposed by the aluminium association of America. In this designation system, the first digit (xxxx) indicates the principal alloying elements, the second digit (xxxx), if different from 0, indicates a modification of the specific alloy. The third and fourth digits (xxxx) are arbitrary numbers given to identify a specific alloy in the series. For instance, in the alloy 5183, the number indicates that it is of the Al-Mg alloy series the 1 indicates that it is the 1st modification to the originally alloy 5083, and the 83 identifies it in the 5xxx series [22].

Aluminium alloys are used in different tempers depending upon the application requirements. The temper designation is always presented immediately following the alloy designation, with a hyphen between the designation and the temper (for example AA6061–T6) the first character in the temper designation is a capital letter indicating the general class of treatment.

The designations are defined and described as follows: F-as fabricated, O-annealed, H-Strain hardened, W-Solution treated, T-Thermally treated to produce stable tempers other than F, O, or H. The first number following the letter (basic Temper) indicates the specific combination of basic operations. In heat treatable aluminium alloys, some of the commonly used tempers are T3 (solution heat treated cold worked and naturally aged), T4 (solution heat treated and naturally aged), T6 (solution heat treated and artificially aged to peak hardness) T7 (solution heat treated and overaged), and T8 (solution heat treated, cold worked and artificially aged to peak hardness) [22]. The mechanical properties of these alloys can be seen below in Table 2.1.

Table 2.1 Mechanical Properties of Aluminium Alloys [27].

Aluminium Alloy	Density (g/cm3)	Tensile Strength (MPa)	Specific strength (Pa・m3/kg)
2024-T3	2.78	485	175
6061-T6	2.7	310	115
7075-T6	2.81	572	204

2.2 WELDABILITY OF ALUMINIUM ALLOY

From the literature it can be observed that the welding of aluminium alloys can give rise to major issues/concerns like I) Hydrogen gas porosity, II) Solidification cracking, III) Liquation cracking in the HAZ and/or partially melted zone (PMZ), IV) Softening or Property degradation in the HAZ and/or PMZ and V) Inferior weld mechanical properties. Regardless of the welding process and aluminium alloy used it is essential that the process parameters are carefully screened to produce defect free welds. As example for minimizing hydrogen gas porosity defects, the base material and filler wire should thoroughly be cleaned just before the welding. Further, as process parameters strongly influence the severity of hot cracking/liquation and HAZ PMZ problems, these parameters should be optimized systematically taking into the account not only weld defects but also weld microstructures and mechanical properties. Hot cracking is one of the major concerns in welding of aluminium alloys, certain alloys are also prone to liquation cracking in the HAZ and PMZ as well, and this is where choice of filler material is critical for conventional welding process.

To address this issue, welding of high strength heat treatable aluminium alloys is welded with low strength non heat treatable filler wire which will compensate the weld composition. In addition to the above technique, pulsed mode is also used sometime. This not only increases the resistance for hot cracking but also decreases the grain size for some aluminium alloys [23]. Few aluminium alloys have serious HAZ liquation cracking issue, it is necessary to use low melting filler wire to ensure that during liquation cracking we can take advantage. Yet another issue in filler material selection is corrosion resistance. While certain filler wires offer satisfactory hot cracking resistance and weld mechanical properties, they suffer from inferior corrosion resistance. Overall filler material must be carefully chosen ensuring satisfactory solidification cracking resistance, weld mechanical properties and corrosion performance [24]. The response of HAZ in aluminium alloy welds is dependent of the base material temper. Both heat treatable alloys and non-heat treatable alloys suffer from a loss of strength in the HAZ in as welded condition. In cold worked non heat treatable alloys, annealing effects in the HAZ account for the loss of strength. In the case of non-heat treatable alloys nothing can be done to recover the properties of HAZ. In heat treatable alloys coarsening of strengthening precipitates occur due to over aging during welding; post welding aging treatment directly cannot help recovering the HAZ properties. This necessitates a full post weld solution treatment followed by aging which however is not practicable in all situations especially for large structures. For heat treatable aluminium alloys, welding in T4 conditions is considered a better strategy. In this case the HAZ does not get over aged significantly, satisfactory weld joint efficiency can be achieved after post weld natural or artificially aging treatments [40].

2.2.2 PROBLEMS ASSOCIATED WITH WELDING ALUMINIUM ALLOYS

Welding of aluminium is “general considered difficult due to high thermal conductivity, electrical conductivity, high thermal expansion coefficient, refractory aluminium oxide formation tendency, and low stiffness” [25]. This results in welding limitations including oxide removal and reduced strength in the weld and heat affected zone (HAZ), which determines the usability and quality of the welds [26]. In addition, hydrogen and other gases show high solubility in the molten state, causing porosity in the weld bead. The main problems that occur when welding high strength aluminium alloys such as 6061 include porosity, oxide film removal during welding, hot cracking, stress corrosion cracking (SCC), and strength loss due to welding. Hot cracking usually occurs in the fusion zone during solidification, or in the HAZs if some of the grains are partially melted during welding; hot cracking in HAZs is typically called liquation cracking. This cracking occurs during the final stages of solidification due to small amounts of segregate-rich low melting point liquid separating solid grains and inducing stresses across adjacent grains. Cracking can be eliminated by several methods, including the use of small additions of elements to produce a small grain size, and using a filler metal with a melting point close to that of the parent metal. Small weld beads generally have better properties and a higher resistance to hot cracking than large weld beads. Stress corrosion cracking (SCC) occurs due to susceptible microstructures, corrosive environments, and tensile stresses [25]. There may be a substantial loss of strength in the HAZ; in cold worked alloys due to recrystallization and in heat-treated alloys due to dissolution of precipitates in 2xxx series and coarsening or over aging of precipitates in 6xxx and 7xxx series alloys. Loss of alloying elements from the weld pool may also occur and result in loss of strength; in particular, magnesium may be lost or oxidized during welding due to its low boiling point.

2.2.3 PROBLEMS ASSOCIATED WITH ALUMINIUM WELDING WIRES

Popular, commercially available welding wires include AA 4043, AA 4943, and AA 5356. The strength and ductility of aluminium alloy joints is largely dependent on filler metals (FMs); the welded zone typically shows the lowest hardness values and resulting tensile strength in the as-welded condition. Low hardness values in the welded zone are typically associated with the lower tensile properties of the filler material selected [21]. The mechanical properties of these popular aluminium alloy fillers can be seen below, in Table 2.

Table 2.2 Mechanical Properties of Popular Aluminium Alloy Fillers

Aluminium Alloy	Density (g/cm3)	Tensile Strength (MPa)
4043	2.68	200
4943	2.68	241
5356	2.66	262

As shown in Table 1 in Section 1, typical base material alloys including AA 2024, 6061, and 7075 have tensile strengths in the heat-treated condition ranging from 310 to 578 MPa [29] — a slight increase from the 310 MPa value of 6061 T6 treated sample. This shows the critical nature of heat treating after welding to recover lost tensile strength. Typically, fillers for welding heat treatable alloys have a lower melting temperature than the base alloy [28]. This allows the base metal alloy adjacent to the weld to solidify before the weld metal, minimizing the stresses on the base metal and reducing tendencies for intergranular cracking, or solidification cracking. However, solidification cracking remains a problem with commonly used filler material. Susceptibility to solidification cracking depends on several factors including the "solidification temperature range, the amount and distribution of liquid at the terminal stage of solidification, the primary solidification phase, the surface tension of the grain-boundary liquid, the grain structure, the ductility of the solidifying weld metal, and the tendency of weld-metal contraction and the degree of restraint" [30]. All these factors are directly or indirectly affected by the weld filler material. Unlike solidification cracking, the fracture surface in liquation cracking does not reveal a dendritic morphology and can occur in the grain interior. One study from Huang and Kou [31] found that if the solid fraction (fs) of the weld filler metal exceeds the PMZ fs during PMZ terminal solidification, "the solidifying and contracting weld metal can become stronger than the PMZ it pulls, and liquation cracking is likely to occur if tensile stresses/strains and liquidation are both significant in the PMZ." In particular, Huang and Kou fabricated full-penetration, circular patch welds in 6061 aluminium with filler metals AA 5356 and AA 4043. This study found severe liquation cracking in the weld made with AA 5356 but not with the weld made with AA 4043. This can be attributed to the AA 5356 filler material having a greater fs than the PMZ fs during PMZ terminal solidification, while the AA 4043 filler had a fs less than the PMZ fs throughout PMZ solidification. A graph of solid fraction versus temperature can be seen below for these two weldments and the 6061-base metal in Figure 3.

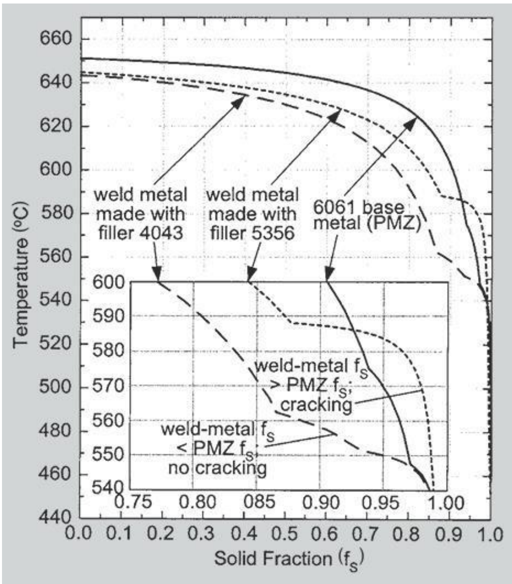


Figure 2.1 Solid fraction vs. temperature for AA 6061 weldments and base material

2.3 ARC WELDING OF ALUMINIUM ALLOY

Arc welding process is a welding process with a formation of an electric arc between an electrode and the metal workpiece by heating of the workpiece metal and cause to melt the filler and base metal together and join. This method was originally developed for aluminum and aluminum alloys. Fusion welding and solid-state welding, or arc welding and friction stir welding (FSW), respectively, are two different methods of joining aluminium alloys. FSW has shown promise as a technique for welding previously unweldable alloys such as AA 7075; however, it is fully mechanized and cannot be used for complicated weld shapes with access restrictions [27]. Thus, arc welding is the preferred method for joining aluminium alloys in complex structures; however, this method experiences problems from the massive heat input and phase transitions. Two popular arc welding methods for joining high strength aluminium alloys are gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW). GTAW is also referred to as tungsten inert gas (TIG) welding, and GMAW is also referred to as metal inert gas (MIG) welding. The primary difference between these two processes is that GTAW uses a non-consumable tungsten electrode, while GMAW uses a consumable electrode. These two processes can be further broken down into subcategories of direct current (DC) arc welding and alternating current (AC) arc welding. AC welding is typically used for fusion welding of aluminum alloys as it supports welding at a higher temperature; when the AC switches to positive, it helps to remove the oxide film on the surface of aluminum and cleans the surface. AC welding also allows for deeper penetration into aluminum plates [28]. Many arc manipulation techniques exist to enhance the properties of aluminum welds, giving the welder superior control over the quality of the weld. Some of these techniques include arc oscillation, which can be used to mitigate hot cracking [29].

However, aluminum alloys remain susceptible to cracking and reductions in strength during the arc welding process.

2.3.1 GAS TUNGSTEN ARC WELDING (GTAW) OR TUNGSTEN INERT GAS (TIG):

GTAW or TIG welding process is an arc welding process uses a non-consumable tungsten electrode to produce the weld. The weld area is protected from atmosphere with a shielding gas generally Argon or Helium or sometimes mixture of Argon and Helium. A filler metal may also feed manually for proper welding. GTAW most called TIG welding process was developed during Second World War. With the development of TIG welding process, welding of difficult to weld materials e.g. Aluminium and Magnesium become possible. The use of TIG today has spread to a variety of metals like stainless steel, mild steel and high tensile steels, Al alloy, Titanium alloy. Like other welding system, TIG welding power sources have also improved from basic transformer types to the highly electronic controlled power source today.

Basic mechanism of TIG welding:

TIG welding is an arc welding process that uses a non-consumable tungsten electrode to produce the weld. The weld area is protected from atmosphere by an inert shielding gas (argon or helium), and a filler metal is normally used. The power is supplied from the power source (rectifier), through a hand-piece or welding torch and is delivered to a tungsten electrode which is fitted into the hand piece. An electric arc is then created between the tungsten electrode and the work piece using a constant-current welding power supply that produces energy and conducted across the arc through a column of highly ionized gas and metal vapours [1]. The tungsten electrode and the welding zone are protected from the surrounding air by inert gas. The electric arc can produce temperatures of up to 20,000oC and this heat can be focused to melt and join two different parts of material. The weld pool can be used to join the base metal with or without filler material. Schematic diagram of TIG welding and mechanism of TIG welding are shown in fig. 4.

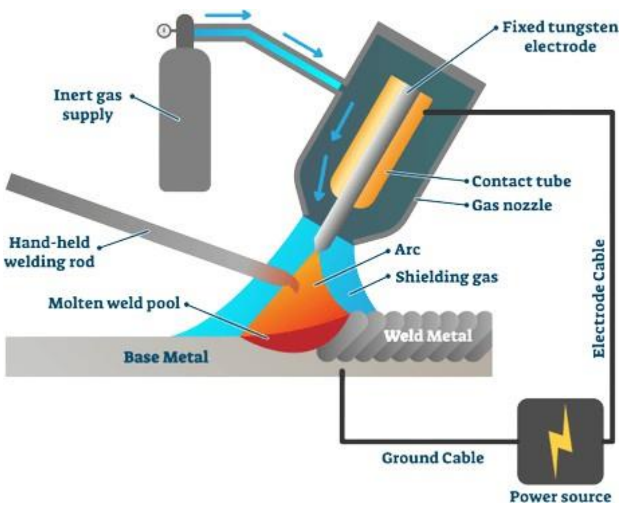


Figure 2.2: Schematic Diagram of TIG Welding System. [Ref: 32]

Tungsten electrodes are commonly available from 0.5 mm to 6.4 mm diameter and 150 - 200 mm length. The current carrying capacity of each size of electrode depends on whether it is connected to negative or positive terminal of DC power source. The power source required to maintain the TIG arc has a drooping or constant current characteristic which provides an essentially constant current output when the arc length is varied over several millimetres. Hence, the natural variations in the arc length which occur in manual welding have little effect on welding current. The capacity to limit the current to the set value is equally crucial when the electrode is short circuited to the work piece, otherwise excessively high current will flow, damaging the electrode. Open circuit voltage of power source ranges from 60 to 80 V.

Table2.3: Electrodes for Aluminum TIG Welding

Pure Tungsten (green)	Most commonly used, least expensive, low current capacity
Thoriated (1% yellow, 2% red)	Recommended for DC welding, difficult to ball tip, high current carrying capacity, good arc starting, resistant to contamination, slightly radioactive.
Zirconiated (brown)	Commonly used and recommended for AC welding with the properties of both pure and thoriated but not radioactive.
Ceriated (gray)	Similar to the physical properties of thoriated but less problems for AC welding and not radioactive. Point stays sharp with inverter on AC.
Lanthanated (black)	Similar to the physical properties of thoriated but fewer problems for AC welding and not radioactive. Point stays sharp with inverter on AC.

Types of welding current used in TIG Welding

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

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

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

d. Alternating Current with Square Wave: With the advent of modern electricity AC welding machines can now be produced with a wave form called Square Wave. The square wave has better control, and each side of the wave can give a more cleaning half of the welding cycle and more penetration [33]. Figure 5 show the effect of dc and ac on weld shape.

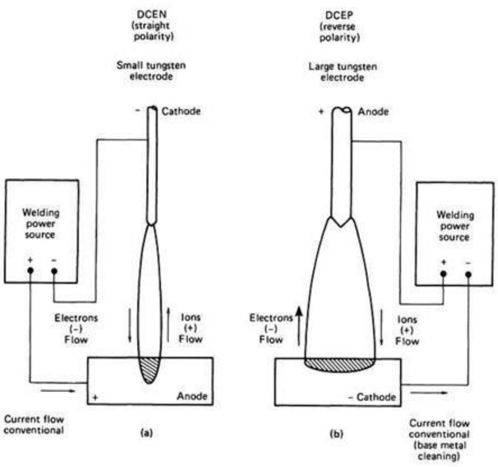


Figure 2.3 – Effect of polarity on GTAW weld configuration when using direct current. (a) DCEN. Deep penetration, narrow melted area, approximate 30% heat in electrode and 70% heat in base metal. (b) DCEP. Shallow penetration, wide melted area, approximate 70% heat in electrode and 30% heat in base metal.

Alternating current is characterized as reversing the polarity of the work and electrode at 60 Hz. The rapidly changing polarity gives a cathodic cleaning action that is beneficial for oxide removal when welding aluminum and magnesium. The alternating currents result in electrode heating during the DCEP portion of each cycle.

This necessitates the use of larger-diameter electrodes, normally made of pure tungsten. Variable polarity welding allows the frequency of polarity switching to be preset. This can produce the cleaning effects to ac welding and the high efficiency of dc welding. Direct current electrode negative is most often used in the GTAW process. This results in maximum application of heat to the work and maximum melting of the work piece. [1] Shielding gases, the original GTAW process used helium as the shielding gas for welding magnesium and aluminum. Today, argon is the predominant shielding gas. Argon is the least expensive of the inert gases used for shielding gas-tungsten arc welds, which is only partially responsible for its widespread use. Argon has a low ionization potential (2.52 × 10 18 J, or 15.7 eV), making it easier to form an arc plasma than with other shielding gases. Argon is approximately 1.4 times heavier than air, so it displaces air, resulting in excellent shielding of the molten weld pool. Helium has an ionization potential of 3.92 × 10-18 J (24.5 eV), which results in more difficult arc initiation and operation at a higher arc voltage. The higher arc voltage, V, results in a higher heat input, Q, for a given arc length and current, I:

$$Q = IVT$$

Copper, aluminum, and other high-conductivity materials. Helium shielding used with DCEN is very effective for welding thick aluminum. [1] Gas purity, most materials can be welded using a welding grade torch gas with a purity of 99.995% or 50 ppm impurities. However, some reactive materials (for example, titanium, molybdenum, and tantalum) require that the contaminant level be less than 50 ppm, which may require certified purity or the use of gas filters and purifiers [22]. Typical flow rates for argon are 7 L/min and 14 L/min for helium.
Backup purge, protecting the molten weld pool from the atmosphere is very important in GTAW. Atmospheric contamination can result in weld cracks, porosity, scaling, and an unacceptable granular appearance. The gas cup on the welding torch is the primary outlet of shielding gas for most GTAW applications. Back side shielding is important because the presence of oxygen can reduce weld metal penetration and result in the effects mentioned above [23]. Balloon and water-soluble paper dams are sometimes used to minimize the volume to be purged. Copper backing bars and ceramics are sometimes used to hold shielding

gas against the back surface of the molten weld and support the molten underbead. Reactive materials and special applications may require more elaborate shielding. This can be in the form of a simple trailing device providing the inert shielding gas or may be as elaborate as a special welding chamber equipped with gas purifiers and analyzers. Specially constructed plastic bags have been used successfully to weld large, irregularly shaped components. [1]

Filler metals, the thickness of the part to be welded will determine the need for filler metal additions. Material thinner than 3.2 mm can be successfully welded without filler metal additions. Filler metal, when needed, can be added manually in straight length or automatically from a roll or coil. The filler metal is normally added cold; hot wire can be used for automatic applications (Fig. 21). A welding insert is replaced filler material of several possible configurations to aid in root-pass welding.[1]

Process parameters of TIG welding

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

a) Welding Current:

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

b) Welding Voltage:

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

c) Inert Gases:

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

d) Welding speed:

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

e) Material:

The most influential parameter can be grouped under base metal properties like material composition and material properties such as thermal conductivity, coefficient of thermal expansion, reaction with atmospheric oxygen and crack sensitivity.

f) Weld geometry:

It is used for the selecting welding process. There can be various joints such as butt, lap, fillet or T-joint. Bevel may be single- V, double-V or U shape. Weld geometry has a direct influence upon weld quality. There can be various Welding positions such as flat, horizontal, vertical, or overhead, etc. Vertical and horizontal welding positions are most used. If the welding position is difficult, then it increases the problems in achieving the required weld quality. Weld bead geometry is also influenced by the position in which the workpiece is held with respect to the welding gun.

2.4 TUNGSTEN INERT GAS WELDING (TIG) OF ALUMINIUM

GTAW is a process that melts and joins metals by heating them with an arc formed between a non-consumable tungsten electrode and metals. Argon is used to provide a shield for the arc and the molten weld pool. This process welds most metals and metal alloys, including aluminum, magnesium, copper, brass, bronze, steels, nickel, and titanium. Most precision parts are gas tungsten arc welded, including batteries, pacemakers, and medical components. An electrical arc is formed between the tungsten electrode and part to be welded using a high voltage to break down the insulating gas between the electrode and the part. Current is transferred through the electrode to create an electrode arc. The metal to be welded is melted by the intense heat of the arc; the argon provides protection for the tungsten electrode and the molten material from oxidization as well as providing a conducting path for the arc current. Welding parameters are of most importance during this process as they directly affect the weld quality. These parameters include current, frequency, voltage, arc length, welding gun speed, welding gun position, shielding gas, and heat input [33]. Alternating current is best adapted for welding aluminum alloys as it allows for balancing of electrode heating and work-piece cleaning effects. The current alternates at a set frequency with no control over time or independent amplitude. Arc current corresponds to the amount of heat the arc

produces from electricity. Frequency directly affects the stability and directionality of the arc; a greater frequency corresponds to greater directionality, deeper penetration, less porosity in the weld metal, and greater welding speed. Arc length is the distance between the electrode tip and the workpiece, and usually ranges from 2 to 5 mm. Successful welding depends on control of both arc current and arc length. If arc length increases, voltage to maintain the arc must also increase; however, heat input to the work piece decreases. The welding gun speed does not affect weld pool formation, only the volume of melted material; this value usually ranges from 100 to 500 mm/min depending on the current, material type, and plate thickness. Electrode angles vary between 30° and 120°; angles between 60° and 120° maintain tip shape and give an adequate penetration depth-to-width ratio. There are their main zones in a gas tungsten arc welded joint: the weld zone, heat affected zone (HAZ), and base metal [34]. The HAZ includes two subzones, one near the weld pool which experiences solution temperature, and one toward the base metal which is exposed to temperatures below the solution temperature and experiences overaging. Behind the subzone experiencing partial melting

completely solidified material called the partially melted zone (PMZ) [30]. A schematic showing these different areas of the weld can be seen below in Figure 2.4.

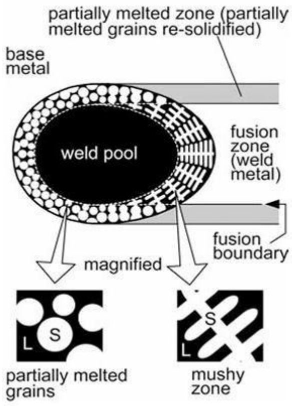


Figure 2.4. Semisolid materials around weld pool of alloy during welding [30]

Heat input is very important during the welding process as the thermal profile in the area near the weld has a significant impact on the formation of the HAZ, its microstructure and mechanical properties including joint strength. Too high of a heat input results in a decrease of the ultimate tensile strength in the welded joint. Microhardness also decreases rapidly with an increase in heat input; an increase in the width of the HAZ and grain coarsening also occur with an increase in heat. Tensile fracture tends to occur in the HAZ with its lower microhardness due to grain coarsening from heat input. However, too low heat input results in pores and partial penetration; high heat input deepens weld penetration, increases welding speeds, and gives better weld quality while also decreasing weld strength of aluminum alloys. Butt joints are typically used for plates of thickness 3 mm; penetration can be achieved at higher thickness by leaving a small gap, or root gap, between the edges to be joined. A backing bar or strip is used to support the root pass where control of the weld bead is difficult on the backside of the butt joint.

Thus, Magesh et al. [13] deployed an automated approach of TIG in welding of aluminium to improve the quality and strength of weld in terms of width and depth of weld penetration. The study ensured certain control parameters such as speed of weld and arc length. The procedure of TIG welding involves the maintenance of the electric arc and the non-consumable tungsten as well as the workpiece. The study further examined the tensile, fracture, hardness, and microstructural properties of the aluminium AA5059 alloy. The result showed that there was about 30% loss in tensile test as the base metal was 385 Mpa and the welded has 268 Mpa. Also, it was observed that there was crack at the weld due to the excessive heat of weld as shown in Figure 3. The study provided a potential information in the successful TIG welding of AA5059 aluminium alloy. It showed that that input parameters such as current, speed and gas flow rate provided the necessary improvement in the mechanical properties [13].

It was reported that the partially melt zone is characterized by a narrow zone outside the weld region where liquation form during weld due to the heating beyond the eutectic temperature. Thus, at this point, the partially melt zone is characterized by eutectic grain boundaries, thus there is a need to understand the content of this eutectic structures since they play a major role in the determination of the mechanical properties of the partially melt zone [10].

The result revealed that there exist a maximum region and clusters of eutectic particles on the weld joint. Additionally, these have significant effect elongation as well as the tensile strength. However, plastic strain dominates the matrix and there was concentration of stress at large eutectic structure [12]. More so, there was tensile cracks, which initiate into the eutectic structure, these cracks propagate into larger cracks, and this caused the eventual fracture of the eutectic structure.

Filler material for GTAW

Filler materials are selected for aluminum welding based on similarity in alloying elements to the base material; in addition, characteristics in the liquid state are important to prevent cracking and properly disperse and fuse with the base material. For Al-Mg-Si alloys, a suitable choice of filler metal can enhance the strength of the fusion zone and HAZ. The most popular, general purpose welding filler wires include AA 4043 and AA 5356, which were specifically designed as welding filler material. AA 4043 contains 5% silicon while AA 5356 contains 5% magnesium. AA 5356 is the preferred material when welding AA 6061 base material, as it is generally stronger and more ductile [26]; however, the silicon in AA 4043 allows it to flow better, have more crack resistance, and better weldability. AA 4943 serves as a kind of hybrid of these two filler metal alloys, with the advantages of AA 4043 and an increase in strength and ductility. AA 4943 is currently suitable for all applications using 4043 — including 1xxx, 3xxx, 4xxx, and 6xxx base alloys; however, it is not recommended for 5xxx series alloys with above 2.5% magnesium, as coarse Mg2Si may form and have a detrimental impact on joint strength and ductility. AA 4943 was designed with magnesium as a strengthening element, which allows it to not be solely dependent on base metal dilution diffusion. Magnesium combines with the available silicon to form Mg2Si, an effective strengthening phase. Magnesium addition is set from 0.1% to 0.5% to achieve a specific amount of Mg2Si precipitation while avoiding the crack sensitivity peak of 1% Mg2Si [35]. Silicon is kept at 5.0-6.0% to maintain free silicon of AA 4043, which is essential for fluidity characteristics and resistance to hot cracking during solidification. Silicon also allows for greater fracture toughness and fatigue performance.

2.7 GAS METAL ARC WELDING (GMAW) OR METAL INERT GAS (MIG):

Metal inert gas welding (MIG) otherwise known as gas metal arc welding is a process in which electric arc is created between the consumable MIG wire electrode and the work material that heat the workpiece to join (fusion). The shielding gas act as a protection from contamination via the welding gun. The welding process involve the supply of constant voltage and direct current supply of power. The transfer of metal in this welding process can be done in four distinct ways, which include short-circuiting, pulsed-spray, spray and globular method. They all have unique properties, advantages and disadvantages irrespective of the desired application [36]. It is also developed for the purpose of welding aluminium and other non-ferrous metals. It is also very fast in the welding of steel compared to the other types of welding process. Presently, it is one of the most welding techniques applied in the industrial welding and fabrication process due to its speed, its adaptability to robotics application and versatility. In contrast to the TIG welding process, it does not involve the use of shielding gas; however, it makes use of electrode wire that is hollow and integrated with flux [37]. It is mostly applied in the sheet metal and fabrication industry as well as in the automobile industry. In addition, MIG welding is not also used in the underwater welding compared to the shield metal arc welding. In the case of MIG welding, the electrode for the welding process is in the form of a metallic alloy (MIG wire) and the choice of this electrode would depend on the chemical composition of the metal to be welded, variation in the process design of the joint and the surface condition of the material. Thus, selection of the electrode greatly influences the mechanical properties of the weld material and quality [38]. However, quality weld using this material should be free from contaminants, porosity, and discontinuities. Thus, electrodes containing small quantity of manganese, titanium, aluminium, and silicon will be the best to avoid porosity due to oxygen presence. Based on variation in the process and base material undergoing welding, the electrode diameter used in this welding must range from 0.7 to2.4 mm and sometimes 4 mm [37]. In the case of quality, there is need to control defects resulting from the presence of dross and porosity in the weld. This can cause weak and ductility in the welded material. For instance, dross is mostly associated with aluminium because of the presence of aluminium oxide or nitride in the electrode or base material. Hence, to avert these problems, continuous brushing and chemical treatment is recommended for the electrode and work material to remove the oxide present during the weld [39]. The main cause of porosity is traceable to the entrapment of gas in the weld pool, and this occur during metal solidification before the escape of gas. However, the gas comes from the impurities present in the shield as well as the workpiece [38].

The quantity of gas entrapped is directly proportional to the rate of cooling of the weld pool. More so, it is worthy of note to say that aluminium has high thermal conductivity, and this make the aluminium weld susceptible higher cooling rates, thus, possibility of increased porosity sets in. however, this can be controlled by adequate cleaning of the workpiece and electrode during the weld process. Also, preheating can control the cooling rate through temperature reduction between the area to be welded and base metal as well. In comparison, tungsten inert gas welding has high versatility, thus, making industry professionals to have several materials joined together. It helps in the heating of a non-consumable tungsten electrode with or without a filler metal. However, it is slower in speed compared to MIG and thus, result in increased lead-time and high cost of production. In addition, operators will need special training to achieve adequate precision and accuracy. Although, control of the welding process can be achieved in this process which will produce precise and strong weld. In most cases, it provides good aesthetic weld [40]. However, metal inert gas welding process is generally deployed into thick and large materials and the consumable wire act as both filler material and electrode. In comparison to TIG welding process, it is much faster and results in minimal lead times and reduced cost of production. In addition to this, it much easier to learn and understand as well as producing weld with less cleaning compared to TIG welding process.

However, in terms of quality of weld, the weld is not as strong and clean like the TIG welding process. Conclusively, aluminium welding is quite difficult compared to welding of steel.

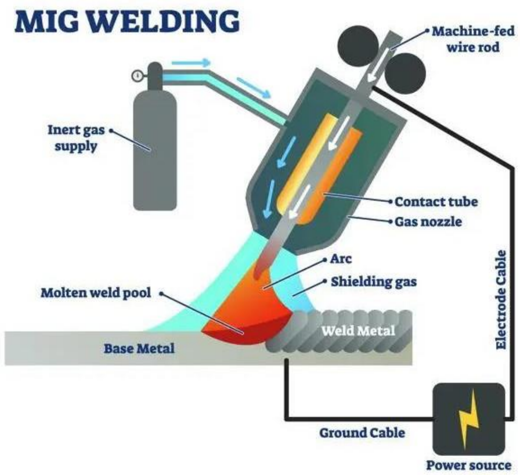
Reason be that aluminium does not behave like steel. For instance, steel will give response during the welding process and one can judge by what you see, however, in the case of aluminium, judgement and experience are the factors to consider in this process [37]. The understanding is that aluminium form oxide layer on its surface, which need adequate cleaning before welding. The oxide layer has a melting point of about 3700 F; however, the

real aluminium beneath the oxide layer will melt at 1200 F. Thus, there is need-increased heat to melt the oxide layer and must be careful as well not to burn the aluminium layer as well.

Thus, to solve this problem, it is important to deploy AC TIG since there is alternation of the current from positive to negative in the electrode.

Basic mechanism of MIG welding:

Principles of operation, GMAW is an arc welding process which incorporates the automatic feeding of a continuous, consumable electrode that is shielded by an externally supplied gas. Since the equipment provides for automatic self-regulation of the electrical characteristics of the arc and deposition rate, the only manual controls required by the welder for semiautomatic operation are gun positioning, guidance, and travel speed. The arc length and the current level are automatically maintained. Process control and function are achieved through these three basic elements of equipment (See Fig. 2.5) the gun and cable assembly performs three functions. It delivers shielding gas to the arc region, guides the consumable electrode to the contact tip and conducts electrical power to the contact tip. When the gun



switch is depressed, gas, power, and electrode are simultaneously delivered to the work and an arc is created.

Figure 2.5 MIG welding (Source: Wu et al., [32]).

The wire feed unit and power source are normally coupled to provide automatic self- regulation of the arc length. The basic combination used to produce this regulation consists of a constant voltage (CV) power source (characteristically providing an essentially flat volt- ampere curve) in conjunction with a constant speed wire feed unit. Some GMAW equipment, however, uses a constant current (CC) power source (characteristically providing a drooping volt-ampere curve) plus an arc voltage-controlled wire feed unit. With this latter combination, arc voltage changes, caused by a change in the arc length, will initiate a response in the wire feed unit to either increase or decrease the wire feed speed to maintain the original arc length setting. In some cases (the welding of aluminum, for example), it may be preferable to couple a constant current power source with a constant speed wire feed unit. This combination will provide only a small degree of automatic self-regulation and can be quite demanding in technique and set-up for semiautomatic welding. However, some users think this combination affords the range of control over the arc energy that is considered important in coping with the high thermal conductivity of the aluminum base metal. [41]

Two sorts of energy resources are used for MIG welding: constant current and constant voltage.

a. Constant Current Power Supply

With this type, the welding present day is installed by way of the ideal placing on the energy supply. Arc length (voltage) is managed by means of the automatic adjustment of the electrode feed price. This type of welding is first-rate proper to large diameter electrodes and device or automated welding, in which very fast exchange of electrode feed price is not required. Most consistent contemporary power resources have a drooping volt-ampere output feature. However, genuine regular current machines are available. Constant modern strength assets aren't generally decided on for MIG welding because of the control wished for electrode feed pace. The structures aren't self-regulating.

b. Constant Voltage Power Supply

The arc voltage is installed with the aid of setting the output voltage at the strength deliver. The electricity supply will deliver the important amperage to soften the welding electrode at the price required to keep the present voltage or relative arc duration. The speed of the electrode pressure is used to manipulate the common welding contemporary. This function is typically desired for the welding of all metals. The use of this type of power supply in conjunction with a regular cord electrode feed results in a self-correcting arc duration device. Motor generator or dc rectifier power assets of either type may be used. With a pulsed direct present day power deliver, the power source pulses the dc output from a low background value to an excessive height price. Because the common power is lower, pulsed welding modern may be used to weld thinner sections than those which can be sensible with consistent dc spray transfer.

Characteristics

The characteristics of GMAW are best described by the five basic modes of transfer which may occur with the process. Three traditional modes of transfer are short circuiting, globular and axial spray. With more recent developments in power source technology, two higher level transfer modes, pulsed spray, and Surface Tension Transfer™ (STT®) have been developed. Even though these power sources are more expensive, the advantages enable users to easily justify the additional cost on many applications. Axial spray and globular transfer are associated basically with relatively high arc energy. With the occasional exception of the spray mode in very small diameter electrodes, both axial spray and globular transfer are normally limited to the flat and horizontal welding positions with material thickness of not less than 1/8 in. (3.2 mm).

SHORT CIRCUITING TRANSFER: Short-circuiting arc welding uses the lowest range of welding currents and electrode diameters associated with MIG welding. This kind of transfer produces a small, speedy-freezing weld pool that is generally appropriate for the joining of thin sections, out-of-role welding, and filling of huge root openings. When weld warmth enter is extraordinarily low, plate distortion is small. Metal is transferred from the electrode to the work simplest at some point of adoration whilst the electrode is in contact with the weld pool. There is no steel switch across the arc hole. The electrode contacts the molten weld pool at a consistent fee in a variety of 20 to over 200 instances each 2nd. As the wire touches the weld metal, the current will increase. It might hold to growth if an arc did not shape. The fee of contemporary growth must be high sufficient to maintain a molten electrode tip until filler steel is transferred. It must no longer arise so fast that it reasons spatter by using disintegration of the moving drop of filler metal. The fee of modern increase is managed by way of adjustment of the inductance in the energy supply. The fee of inductance required relies upon on both the electric resistance of the welding circuit and the temperature variety of electrode melting. The open-circuit voltage of the strength supply ought to be low sufficient in order that an arc cannot maintain underneath the present welding situations. A part of the electricity for arc preservation is furnished by means of the inductive storage of power during the length of quick-circuiting. As steel transfer best happens throughout short- circuiting, defensive gas has very little effect on this sort of transfer. Spatter can arise. It is normally induced either by gasoline evolution or electromagnetic forces on the molten tip of the electrode.

GLOBULAR TRANSFER: With a superb electrode (DCRP), globular switch takes vicinity whilst the contemporary density is incredibly low, irrespective of the kind of protecting fuel. However, carbon dioxide (CO_2) protecting yields this kind of switch in any respect usable welding currents. Globular switch is characterized by way of a drop length of more diameter than that of the electrode. Globular, axially directed transfer may be finished in a significantly inert gas protect without spatter. The arc duration needs to be lengthy enough to guarantee detachment of the drop before it contacts the molten steel. However, the ensuing weld is probable to be unacceptable due to lack of fusion, insufficient penetration, and excessive reinforcement. Carbon dioxide protecting constantly yields non axially directed globular switch. This is because of an electromagnetic repulsive pressure appearing upon the lowest of the molten drops. Flow of electric present day thru the electrode generates numerous forces that act at the molten tip. The maximum essential of those are pinch pressure and anode reaction pressure. The value of the pinch pressure is a direct feature of welding modern-day and twine diameter and is normally responsible for drop detachment. With CO_2 protective, the cord electrode is melted by using the arc warmth conducted through the molten drop. The electrode tip isn't enveloped by using the arc plasma. The molten drop grows until it detaches through short circuiting or gravity.

SPRAY TRANSFER: In a fuel shield of at least eighty percent argon or helium, filler steel transfer changes from globular to spray type as welding current increases for a given size electrode. For all metals, the alternate takes vicinity at a cutting-edge fee called the globular-to-spray transition present day. Spray kind switch has an average exceptional arc column and pointed wire tip associated with it. Molten filler metallic transfers across the arc as first-rate droplets. The droplet diameter is identical to or less than the electrode diameter. The steel spray is axially directed. The reduction in droplet size is likewise accompanied through a boom in the price of droplet detachment, as illustrated in discern 10-forty-seven. Metal switch rate might also range from less than a hundred to numerous hundred droplets per 2d because the electrode feed rate will increase from approximately one hundred to 800 in./min (forty-two to 339 mm/s).

2.7.1 METAL INERT GAS WELDING (MIG) OF ALUMINIUM

Light weight low-cost components are in increasing demand in the automobile industry and a promising material for this industry is the aluminium alloy because of its light weight and availability compared to other metals [43]. Also, they have good castability, high strength and corrosion resistance. However, aluminium need to be combined with other metals by joining techniques in order achieve better applications and performance. The presence of excessive hydrogen content in the die casting of aluminium, which is caused by rapid solidification during the production of aluminium via casting process, has a major consequence. This includes porosity and results in the deterioration in the mechanical properties of the aluminium alloy [40]. To resolve this problem, ultrasonic frequency pulse is introduced into the MIG welding process for the purpose of controlling the porosity of the joints via stirring and mixing thereby, increasing the tensile strength. To this end, Ye et al. [44] enhanced the joint of two dissimilar aluminium alloy joint by bonding them together using MIG welding integrated with ultrasonic frequency pulse. The result revealed a decrease in the hydrogen porosity in the joint. Thus, there was increase in the tensile strength of the joint, which reach about 185 %. Thus, the ultrasonic frequency pulse with integrated metal inert gas welding process was utilized to bond two dissimilar aluminium alloy. This revealed good microstructures and improvement in the tensile properties. Furthermore, a major reason why aluminium is desired in the automobile manufacturing is in the energy savings and low emission due to its lightweight when compared to steel especially in the manufacture of the car body. Thus, excellent, and superior performance of aluminium alloy have increased its trend of application in the automotive industry. However, there are major limitation that have posed to be a challenge in the joining of aluminium, and these include variation in thermal properties of dissimilar materials, low solubility, and generation of brittle compounds. To this end, Wan et al. [43] proposed a novel MIG welding and brazing process of aluminium and steel by integrating external magnetic field. This was done to enhance the arc and the droplet to move along the welding direction with an alternative electromagnetic force, which is perpendicular to the force of welding. The result showed that there was improvement in the spread ability of the molten alloy, which was occasioned by the increased current level. There was also an enhancement in the tensile strength of the weld joint because of the spread ability of the molten metal under the action of EMF. In the study of Arunakumara et al. [45], it was established that aluminium 6000 series are used several industries due to its excellent corrosion resistance, weldability and relative low cost. The use of conventional fusion welding process causes porosity, penetration of slag as well as incomplete integration of the aluminium alloy. Thus, MIG welding process is the best for the fusion welding since it will protect the joint from the impurities resulting from the welding process. Thus, the study compared the microstructural evolution and the fatigue properties of two dissimilar aluminium alloy Al 6061 T-6 and Al 6082 T-6 bonded together using MIG and friction welding processes [42]. The study examined the tensile strength of both alloys that depends on the process parameters selected during the welding process. The result showed that the MIG welding process gave a better yield compared to the friction stir welding.

It has been established that the geometry of the weld bead serves as an important factor that determines the strength, mechanical properties and performance aluminium alloy produced by metal inert gas welding especially in today's fabrication industry. Based on this assertion, Sharma et al. [41] predicted the weld bead geometry via parameter optimization in other to provide weld of high reliability. Mathematical relationship linking the input parameters like feed rate of the wire, speed, voltage torch angle depth of penetration width of weld as well as reinforcement height was developed. The study further deployed statistical approach like central composite design and analysis of variance as well as response surface methodology for the analyses. It was observed that the weld bead geometry influenced the mechanical properties as well as quality of the weld joint [45]. The result also indicated that the bead geometry is a function of input parameter, and this parameter can be obtained from the optimal combination of the input parameters. In the case of joining aluminium and magnesium alloys, which are commonly deployed in the automotive and aerospace industries due to their lightweights and ease of casting and workability, is a complex one. The reason being that the reaction between aluminium and magnesium bring about the formation of intermetallic compounds that deteriorate the mechanical properties at the joint [41].

2.8 WELD STRUCTURE

In the welding process, because of the arc, heat is generated on the weld pool and some regions are directly affected by this heat generation and some other regions are yet less affected. On this respect, there are three main regions in the weldment that can be distinguished either with naked eye or with chemical etching. The weldment regions are named as Weld Metal (WM), Partially Melted Zone (PMZ) and Heat Affected Zone (HAZ).

The boundary that separates the weld metal and the base metal is called the fusion line (FL) where the temperature reaches the liquidus temperature (TL). The region which is affected by the heat evolved during welding and between the weld metal and base metal is called Heat Affected Zone (HAZ).

The region in HAZ that starts from fusion line and ends at the point where solidus temperature (TS) is reached is called Partially Melted Zone (PMZ) where the heat is too low to melt tough high enough to alter the microstructure. [46]

2.8.1 WELD METAL

Heat required for melting is generated by the arc burning between welding torch and base metal. Since the solution of weld metal, composition, heat distribution, and microstructure of weld metal are in direct relation with weld parameters like welding current, welding speed and so, base metal grains around the weld pool act as nucleation sites during solidification of the weld metal. Accordingly, solidification mode together with microstructure of the WM basically depends on the solute distribution, chemical composition, cooling rate and growth rate. In Figure 5, the effect of temperature gradient and growth rate on solidification mode can be seen. Growth rate (R) and temperature gradient (G) maps the solidification mode and the microstructure size also described in Figure 8 and G/R determines the solidification mode and GxR represents the size of the solidification microstructure. Considering the solidification mode indirectly that is G/R ratio, it is affected by heat input and welding speed, meaning, increasing line energy with constant weld speed, in other words, only an increment in heat input, results with decrease in temperature gradient, thus G/R ratio decreases. Decline of the G/R ratio changes the solidification mode (microstructure) from cellular to dendritic. [47]

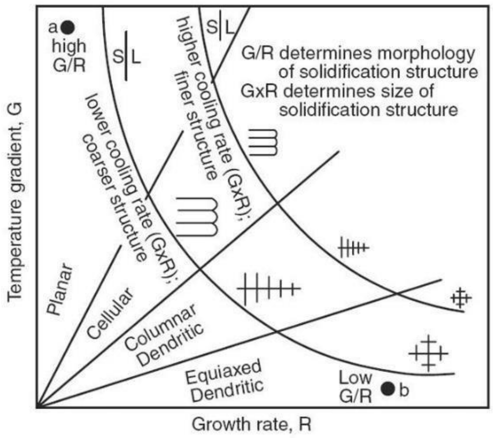


Figure 2.6 Weld metal solidification affected by cooling rate and growth rate. [47]

Further, the size of the microstructure is also affected by heat input and welding speed such as increasing cooling rate decreases the dendrite arm spacing. The cooling rate can also be altered by dropping the line energy (Q/V) where Q represents the heat input and V represents the welding speed. Therefore, decreasing the line energy results with finer microstructure.
When it comes to discuss the growth rate and temperature gradient, they both change along the weld pool boundary starting from the centre line and ended in fusion line. For this reason, weld pool boundary plays an important role for changing the solidification mode and welding speed affects the growth rate, so it changes from V to zero from centreline to fusion line that can be seen in Figure 2.7.

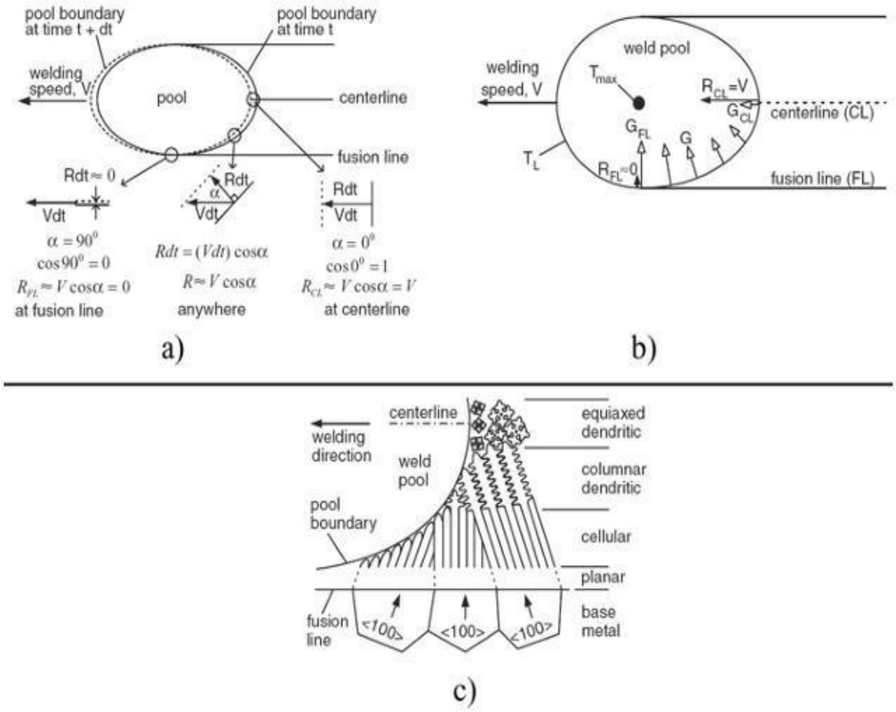


Figure 2.7 a) Growth Rate b) Temperature Gradient c) Solidification mode along the weld pool. [47]

Weld pool shape is also affected by welding parameters. Low weld speeds together with low heat input results more elliptical weld pool whereas high weld speeds with high heat input results tear dropped shape weld pool which yields heterogeneous nucleation at the centre of weld.

2.8.2. PARTIALLY MELTED ZONE (PMZ)

The region in HAZ that starts from fusion line and ends at the point where solidus temperature (TS) is reached is called Partially Melted Zone (PMZ) where the heat is too low to melt tough high enough to alter the microstructure. [46,47] PMZ is a detectable region in aluminum alloys due to the wide solidification range. As far as it is known that welding harms the strength of the metals, especially aluminum alloys. Strengthening mechanism of aluminum alloys can occur with age hardening, work hardening and other different methods. These methods help to recover the strength of the alloys. 6xxx series aluminum alloys, that are heat treatable, loose their strength after welding, therefore, by post weld heat treatment processes, recovery of mechanical properties can be derivable. Since heating rate is very fast during welding, various liquation mechanism results from equilibrium condition. Research state approximately five different mechanisms depending on the alloy composition. [46-48] First mechanism can be applicable for an alloy having composition of C2 that can be seen in Figure 2.8a. The second mechanism that can be seen in Figure 2.8b, at room temperature AxBy and α phases are present but during the welding procedure the eutectic reaction occurs at eutectic temperature (TE) between these phases therefore C2 also contains α+ AxBy. The third mechanism is named as constitutional liquation. [47, 49] In this mechanism, C1 contains AxBy particles and in equilibrium condition when temperature is Ts, AxBy dissolves in α phase, hence, no liquation is seen up to solidus line. On the other hand, if high heating rates is seen, AxBy particles can remain without dissolution in α phase during welding and for this reason at TE liquation occurs between AxBy particles and α phase because of eutectic reaction.

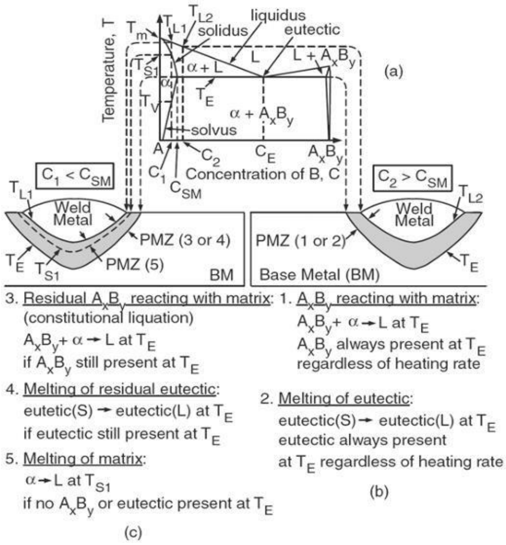


Figure 2.8 Liquation mechanisms solid solubility limit and above the solid solubility limit respectively. [47]

2.8.3. HEAT AFFECTED ZONE (HAZ)

Heat Affected Zone (HAZ) is the region between partially melted zone and the base metal. Hence, it is affected by the high temperatures during welding but there occurs no melting across HAZ. However, because of the heat input, the base metal microstructure changes and previously gained good mechanical properties are affected negatively. Therefore, in order to recover the mechanical properties in HAZ, post weld heat treatments are necessary.

2.9. ALUMINUM WELDING DISCONTINUITIES

Although aluminum alloys have wide range of application areas, considering the welding of aluminum alloys, it is known that it is a limited process. The reason for these limitations stems mainly from the intrinsic defects (hot tearing, inclusions, and hydrogen cracking) associated with fusion and solidification. Discontinuities coming from welding process itself such as undercut, porosities, lack of penetration, arc strike, incomplete fusion, overlaps, melt-

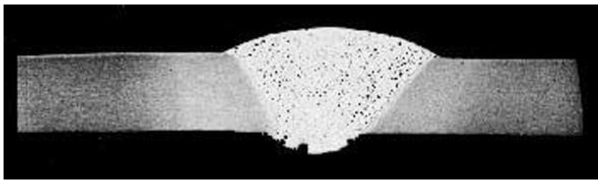


Figure 2.9 Finely distributed porosity in a weld groove [49]

through shrinkage voids, oxide inclusions and so can be seen. [47,50] The summary of problems with solutions can be seen in Table 2.4 Discussing the porosity as a discontinuity in aluminum alloy welds, which was seen during this study, it is mainly a problem confined to the weld metal and occurs as a result of the dissolved gas in the molten weld metal becoming trapped as it solidifies thus, forms gas cavities can be seen in Figure 2.9. [49]

Therefore, porosity in welds can range from being extremely fine micro-porosity, up to coarse pores. It is known that, increasing the arc current increases the temperature, herewith increases the temperature of the weld pool, thereby, increases the rate of absorption of hydrogen in the molten metal, as a result, amount of porosity increases. Conversely, changing the weld position to flat position again heat input increases but porosity may decrease. If the rate of gas evolution from the weld exceeds the rate of absorption, similar to say that, slowing the rate at which the weld freezes allow hydrogen to bubble out of the weld metal. [49]

Table 2.4 Typical Welding Problems in Aluminum Alloys [47]

TYPICAL PROBLEMS	ALLOY TYPE SOLUTIONS	ALLOY TYPE SOLUTIONS
Porosity	Al-Li alloys (severe)	Surface scraping or milling Thermovacuum treatment Variable-polarity keyhole PAW
	Powder-metallurgy alloys (severe)	Thermovacuum treatment Minimize powder oxidation and hydration during atomization and consolidation
	Other types (less severe)	Clean workpiece and wire surface Variable-polarity keyhole PAW
Solidification cracking in FZ	Higher-strength alloys (e.g., 2014, 6061, 7075)	Use proper filler wires and dilution In autogenous GTA welding, use arc oscillation or less susceptible alloys (2219)
Hot cracking and low ductility in PMZ	Higher-strength alloys	Use low heat input, Use proper filler wires Low-frequency arc oscillation
Softening in HAZ	Work-hardened materials Heat-treatable alloys	Use low-heat input Post weld heat treating

CHAPTER 3:

MATERIALS AND METHODS

CHAPTER 3: MATERIALS AND METHODS

3.1 INTRODUCTION

The experimental work and methodology section explains the empirical procedure followed in this study, which is aimed at comparing TIG and MIG welding techniques in aluminum 6061 alloy material. This research focuses on the welding behavior of aluminum 6061 because of the material's importance in applications such as aerospace, automotive, and marine industries. This chapter gives details of the materials used, equipment and methods used in the experiments. It also explains how to obtain the aluminum 6061 samples, which welding consumables to use, and the recommended parameters for both TIG and MIG welding. Moreover, it expounds the approaches to testing and analysis of weld quality, mechanical characteristics, and microstructures.

It is therefore important to observe several factors that enable the experiment to produce accurate and consistent results. This section also discusses the safety measures taken during the welding process and the techniques used to confirm the reliability of the conclusions. This purpose of this research is to develop a clear understanding of TIG and MIG welding techniques based on a structured approach and generate significant findings that can be beneficial for welding practitioners and engineers.

3.2 BASE AND FILLER MATERIAL

The materials used in this study primarily consist of aluminum 6061 alloy and welding consumables specific to the TIG and MIG welding processes. The selection and preparation of these materials are critical to ensure reliable and consistent results.

Aluminium 6061 Silicon as its major alloying elements. Originally called "Alloy 61S. It has good mechanical properties, exhibits good weld ability, and is very commonly extruded (second in popularity only to 6063). It is one of the most common alloys of Aluminium for general-purpose use.

3 mm thick sheets of 6061-O Aluminium alloy in T6 condition was used in the present study. The nominal chemical composition of the base material is listed in the Table 3.1.

Table 3.1: Chemical composition of AA 6061 alloy (wt. %)

Si	Fe	Mn	Mg	Zn	Cr	Cu	Al
0.65	0.31	0.12	1.05	0.01	0.25	0.27	Balance

Table 3.2 Chemical Composition of (wt.%) of ER4043 filler material

Si	Mg	Cu	Fe	Mn	Zn	Ti	Al
5.6	0.05	0.3	0.8	0.05	0.1	0,02	Balance

Table 3.3: Thermo-Physical Properties of Aluminum Alloy 6061

Density	2713, kg/m³
Specific heat	0.896 J/g.°C
Thermal conductivity	167 W/ (m².K)
Electrical conductivity	43 (% IACS)

Table 3.4: Mechanical Properties of Al 6061

Yield strength	55-85 MPa,
Ultimate tensile strength	125 to 190 MPa,
Elongation at fracture	18%-25%
Shear strength	70-85 MPa
Vickers Hardness	35-45 HV
Modulus of Elasticity	68.9 GPa

3.3 SAMPLE PREPARATION

For the present study plates of the aluminium alloy of 3 mm thickness were cut into specimens of 100 mm X 100 mm size. The edges of the samples were mechanically ground to remove sharp edges and before welding, specimens were cleaned with stainless steel wire brush followed by acetone wash to remove oxide layer and dirt from the surfaces of the specimen. These specimens were directly used for Bead on Plate experiments and for butt welding experiments two such pieces were joined without any joint preparation. This angled edge created a single V groove butt joint when two plates were welded together along the angled edges; this joint is easily designed and uses a minimum amount of material. Following sanding and polishing to create angled edges, the edges were then rubbed with scouring pads to further smooth out the welding surface, and then finished with acetone to remove any remaining debris. This ensured a smooth, clean surface along the single-V butt joint.

3.4 EXPERIMENTAL SETUP FOR TIG

The experimental procedure is the set of steps that were followed during the testing and analysis of the (TIG) welding parameters for 6061T6 aluminum alloy. It includes the preparation of the welding samples, the setup of the welding equipment, the selection and adjustment of the welding parameters, and the execution of the welding process as shown in the Figure 3.1 represent the Welding Machine used in Experimental work. The procedure also involves the recording of various welding in puts parameters such as welding current, welding speed, gas flow rate, and electrode type. Figure3 shows the shape of the designed welding lines and their butt joints after welding operations. The collected data is then analysed and evaluated to determine the Optimal TIG welding parameters for 6061 aluminum alloy. Using a mechanical machining process, 6061 aluminum alloy sheets with a thickness of 3 mm were cut to the needed dimensions of 100 × 100 mm for use as the experimental base metal in this analysis. All surfaces are washed to remove oxides, grime, and rust prior to welding. Table 3.4 and Table 3.2 demonstrate the mechanical properties and chemical composition of 6061 Aluminum alloys, respectively. For welding alloy 6061 aluminum, ER 4043 welding wire with a 2.5 mm diameter was utilized as filler material. This welding wire, containing 5% silicon, is generally preferred due to its superior flow ability, crack resistance, ease of welding, and aesthetic weld results. However, the suitability of this welding wire de pends on the particular application, as it has both advantages and disadvantages. Compared to other wires that are suitable for the same base metal, ER 4043 is less prone to smut formation and crater the cracking, and it exhibits reduced crack sensitivity, making it an ideal choice to avoid stress corrosion cracking. Table 3 displays the results of the chemical examination of the electrode welding.

3.4.1 EQUIPMENT

ibell t250-106 is a TIG welding system especially designed for industrial use and for welding. The equipment consists of a power source, panel and TIG-welding torch. The power source is a multifunctional and can be used for MMA welding also, only welding torch need to be changed. The welding torch is cooled with gas.

Figure 3.1 For TIG and MMAW welding ibell t250-106

Model:	iBell T250-106
Type:	Inverter ARC Welding Machine
Input Voltage:	220V AC ± 15%, Single Phase
Frequency:	50/60 Hz
Rated Input Power Capacity:	7.3 kVA
Output Current Range:	20-250 Amps
Duty Cycle:	60% at 250A
No Load Voltage:	60V
Power Factor:	0.93
Efficiency:	85%
Insulation Class:	F
Protection Class:	IP21S
Cooling Type:	Forced Air Cooling

Table 3.5 Technical specification of ibell t250-106

3.5 PARAMETERS FOR TIG WELDING

After sample preparation, Aluminium plates are fixed in the working table with flexible clamp side by side and welding done so that a butt join can be formed. TIG welding with Alternate Current (AC) was used in experiments as it concentrates the heat in the welding area. Zirconated tungsten electrodes of diameter 2.4 mm were taken as electrode for this experiment. The end of the electrode was prepared by reducing the tip diameter to 2/3 of the original diameter by grinding and then striking an arc on a scrap material piece. This creates a ball on the end of the electrode. Generally, an electrode that is too small for the welding current will form an excessively large ball, whereas too large an electrode will not form a satisfactory ball at all.

For the first phase of experiment welding parameters selected are shown in table 3.6 Before performing the actual experiment, a few trial experiments have been performed to get the appropriate parameter range where welding could be possible and no observable defects like undercutting and porosity occurred. Here, the shielding gas (helium), welding voltage, and welding speed were constant. The heat input (Q) of welding is determined by-

$$Q = \eta \frac{UI}{V}$$

where U is the welding voltage, V is the welding speed, I is the welding current, and η is the efficiency of TIG welding (η =0.65) [51]

Table 3.6 Welding parameters for TIG

Parameters	Range
Welding current	110 A
Speed	230 mm/min
Arc Length:	3 mm
Electrode Diameter:	2.4 mm
Gas flow rate	10 L/min
Current type	AC
Dimension	100 x 100 x 3 mm
Filler Rod Diameter:	2.4 mm
Heat Input	.164 J/mm

3.5 EXPERIMENTAL SETUP FOR MIG

The experiments are carried out on Semi-automatic Metal Inert Gas arc welding machine model pro mig 530 kemppi in a single run shown in figure 3.2 Argon gas with gas flow rate 15 L/min used as a shielding gas to protect the arc and weld bed from atmospheric contamination. 1.2 mm diameter ER 4043 Filler wire used to weld the test specimens. The material chosen for the present study was aluminium alloy 6061. Sample of 100 x100 x3 size has been used as a work piece material. 60^{o} V edge preparation was made on these specimens. Root gap and root face kept 1 mm each. Welding process parameters taken as per Table 3.8. Welding current, Welding Voltage varied and Welding speed, Gun Nozzle tip to plate distance, and gas flow rate remained constant. The experiment is carried out within the welding current 125 A. Tensile samples were prepared as per ASTM-E8/E8M-09 Standard from the MIG welded specimens. Tensile test was made using Universal Testing Machine (UTM) with hydraulic grip. The microstructure of all the specimens were carried out using Metallurgical microscope with Image Analyzer System, the Microhardness study was carried out using Digital Vickers Microhardness tester.

3.3.1 EQUIPMENT

pro mig 530 kemppi

The ProMIG 530 Kemppi is a high-performance MIG welding machine designed for professional and industrial applications. Known for its robust construction and advanced technology, the ProMIG 530 Kemppi offers exceptional welding performance and versatility. Kemppi, a renowned name in the welding industry, has engineered this machine to meet the demanding needs of modern welding tasks. With features like digital controls, a wide range of output currents, and compatibility with various materials, the ProMIG 530 Kemppi stands out as a reliable and efficient choice for welders seeking precision and durability in their work.

Figure 3.2 For pro mig 530 kemppi MIG welding were used.

Promig 530		
Working voltag (safety voltage)		50 VDC
Max. load (nominal values)		100 W
Kuormitettavuus (nimellisarvot)		
	60 % ED	520 A
	100 % ED	440 A
Operation principle		4 roll feed
Diameter of feed roll		32 mm
Wire feed speed I		0...18 m/min
Wire feed speed II ¹)		0...25 m/min
Filler wires	ø Fe, Ss	0,6...2,4
	ø Cored wire	0,8...2,4
	ø Al	1,0...2,4
Wire reel	max. weight	20 kg
	max. size	ø 300 mm
Gun connector		Euro
Operation temperature range		-20...+40 °C
Storage temperature range		-40...+60 °C
Degree of protection		IP 23 C
Dimensions without handles	length	640 mm
	width	230 mm
	height	430 mm
Weight		21 kg

Table 3.7 Technical speicifcation of pro mig 530 kemppi

3.6 PARAMETERS FOR MIG WELDING

The experiments are carried out on Semi-automatic Metal Inert Gas arc welding machine in a single run shown in figure 3.2 Argon gas with gas flow rate 25 L/min used as a shielding gas to protect the arc and weld bed from atmospheric contamination.

1.2mm diameter ER 4043 Filler wire used to weld the test specimens. The material chosen for the present study was aluminium alloy 6061. Sample of 100mm x100mm x 3mm size has been used as a work piece material. 60o V edge preparation was made on these specimens. Root gap and root face kept 1mm each. The heat input is calculated using Eq.

Heat input; $HI\ (kJ/mm) = \eta \frac{VI60}{S1000}$

where Vis the arc voltage in volts, I is the average arc current in amperes, S is the welding speed in millimetres per minute and η is the thermal efficiency factor and it is constant which is equal to 0.8.

Welding Voltage varied and Welding current, Welding speed, Gun Nozzle tip to plate distance, and gas flow rate remained constant.

Table 3.8 Welding parameter for MIG welding

Parameters	Range
Welding current	125 A
Voltage	16.1 V
Speed	400 mm/min
Heat Input	242 J/mm
Gas flow rate	15 L/min
Wire feed speed	5600 mm/min
Dimension	10 x10 x 3

3.7 MICROSTRUCTURE DEVELOPMENT

To make the sample ready for metallographic investigation, there are steps that must be followed to ensure a healthy and great analysis my sample. The steps that have been followed during the examination, are mentioned as follows.

Aim

Preparation and study of the Microstructure of different welded sample. To

Learn the preparation of specimen for microscopic observation.

3.7.1 SECTIONING

Aluminum alloys can be sectioned by any standard cutting method; however, the cutting must not alter the structure or the configuration of the specimen in the plane to be examined. Because many aluminum alloys are soft, sawing or shearing should be done at a distance from the plane to be polished and then the intervening deformed material removed by wet grinding and polishing. An abrasive saw permits cutting closer to the plane of polishing. The temperature of the metal must not increase sufficiently during cutting to affect adversely the results of the examination. Because the grains in wrought aluminum alloys are rarely equiaxed, sections for determining grain size must be defined regarding the principal direction of working.

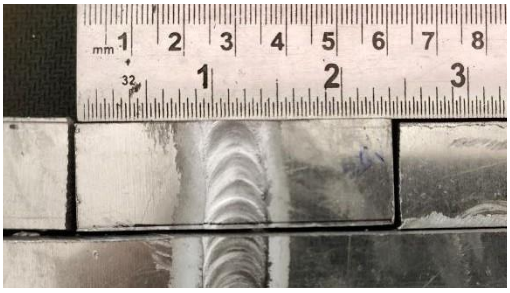


Figure: 3.3 Sectioned welded sample

3.7.2 SAMPLE SURFACE POLISHING

The goal of the surface polishing is to end up with a planar cross section of sample free from scratches or disturbed metal introduced by the cutting and sectioning. This process is a stepwise process that can be broken into three loosely separate parts: grinding, coarse polishing, and final polishing.

3.7.3 GRINDING

Aluminum alloys can be ground using the same general techniques for all metals. Because aluminum alloys can be ground readily with various abrasives, selection is made on an individual basis. Generally, grinding is performed in successive steps using silicon carbide

abrasive papers of 180, 220, 320, 400, and 600 grit. The first step in preparing your sample is to ensure that you have a flat surface to begin with. A water-cooled abrasive grinder is available to form a flat initial surface from which to begin. After getting a flat sample on the belt grinder, WASH sample thoroughly. The hand lapping station has four graded abrasive papers to produce a sequentially finer surface finish. Be sure the water is turned on and flowing uniformly over the abrasives. Start with the coarsest grit (240) and, using a firm and uniform pressure, slowly move the specimen forward and back across the abrasive. This will produce parallel scratches of uniform size. Continue this step until the entire surface of your sample is flat and contains only scratches of the size of 240 grit abrasive. When the sample is flat and the only scratches remaining are those due to the 240-grit abrasive, WASH your sample and your hands thoroughly, and move to the 320-grit abrasive. Repeat this procedure for the 400 grit and the 600-grit abrasive, checking after each step to be sure that only those scratches remain that are due to the smallest grit.

3.7.4 POLISHING

This wheel uses a 0.05 micrometer A1203 abrasive in a water suspension. At this point, the sample will be very smooth to the eye and even the oils and dirt on your fingers will scratch it with larger scratches than the abrasive. Do not touch the sample surface from this point on. The last step in the process is to etch the sample to bring out the microstructure. Use a cotton swab and a petri dish for the etching. Gently swab the surface of your sample with the etchant. Roughly spreading the etchant will scratch your surface. Let the etchant stand for 15 seconds or

Figure 3.4: cloth polishing.

so, and rinse the sample with water to stop the etching, and rinse again with methanol. Rinse the swab with water and throw it into the trash bin. Examine specimen under the microscope. You may require several etching steps to bring out the microstructure. If the sample is over-etched, repeat the final polishing step and re-etch for a shorter time. Samples to be examined at high magnification generally require shorter etching times than those to be viewed at lower magnifications, after last polishing stage the sample looks mirror like.

3.7.5 ETCHING

Metallographic Observation

Observe microstructure, Place specimen on metallograph and adjust magnification, focus and positions adjust microscope High magnification - to study phases and Low magnification -to study grain size.

In this laboratory, you will report the microstructures of prepared samples in specific formats. You will be expected to sketch the microstructure that you see under the microscope by hand. In sketching the microstructure there are several things to keep in mind. First, the magnification that you use depends upon the scale of the microstructure you are looking for. It is important to know in advance of the lab class what the expected microstructure for your samples are and at what scale they should appear. In sketching the microstructure, you should indicate only the important features of the structure that you observe-don't make a photographic reproduction of the microstructure. Simple sketches show that you know what the important structures are and have identified them in the cross section.

Figure 3.5: microphotography set up of laboratory.

3.8 MICROHARDNESS TESTING:

Hardness testing of welded joints is widely used as a rapid measurement of mechanical properties across the varying microstructures of the welded region. It allows local regions and individual microstructures to be compared for strength, because strength is correlated to hardness. Microhardness testing of welds requires preparation of a small region of the surface. The major techniques are Brinell testing, which uses a spherical indenter, and Rockwell testing, which uses a diamond penetrator or a sphere. The Brinell indentation is typically 2 to 6 mm in diameter while the Rockwell indentation is much smaller but still is visible, unaided. Microhardness testing results can be limited by the microstructural gradients around the welds. A result of 240 HB may represent a hardness for one uniform microstructure or an average over the regions deformed by the indenter. Welds and HAZs often have gradients of microstructure and chemistry that can cause variations in hardness across the indentation. Interpretation of the hardness from the impression may be made more difficult if there is a large gradient in the hardness of the material under the indenter. This can result in noncircular Brinell impressions and Rockwell tests with the deepest point not under the deepest point of the indenter. The hardness number is based on measurements made of the indent formed in the surface of the test specimen. It is assumed that recovery does not occur upon removal of the test force and indenter, but this is rarely the case. For the Vickers test, both diagonals are measured and the average value is used to compute the Vickers hardness (HV). The hardness number is based on the surface area of the indent itself divided by the applied force, giving hardness units of kgf/mm2. In practice, the test units kgf/mm2 (or gf/ m2) are not reported with the hardness value. Microhardness testing involves indenting the material surface with a specialized indenter, typically made of diamond, under a controlled load for a specific dwell time. The resulting indentation is then measured using a high-powered microscope. Based on the indentation geometry and applied load, The Vickers number (HV) is calculated using the following formula: HV = 1.854(F/D2),

With F being the applied load (measured in kilograms-force) and D2 the area of the indentation (measured in square millimeters). The applied load is usually specified when HV is cited.

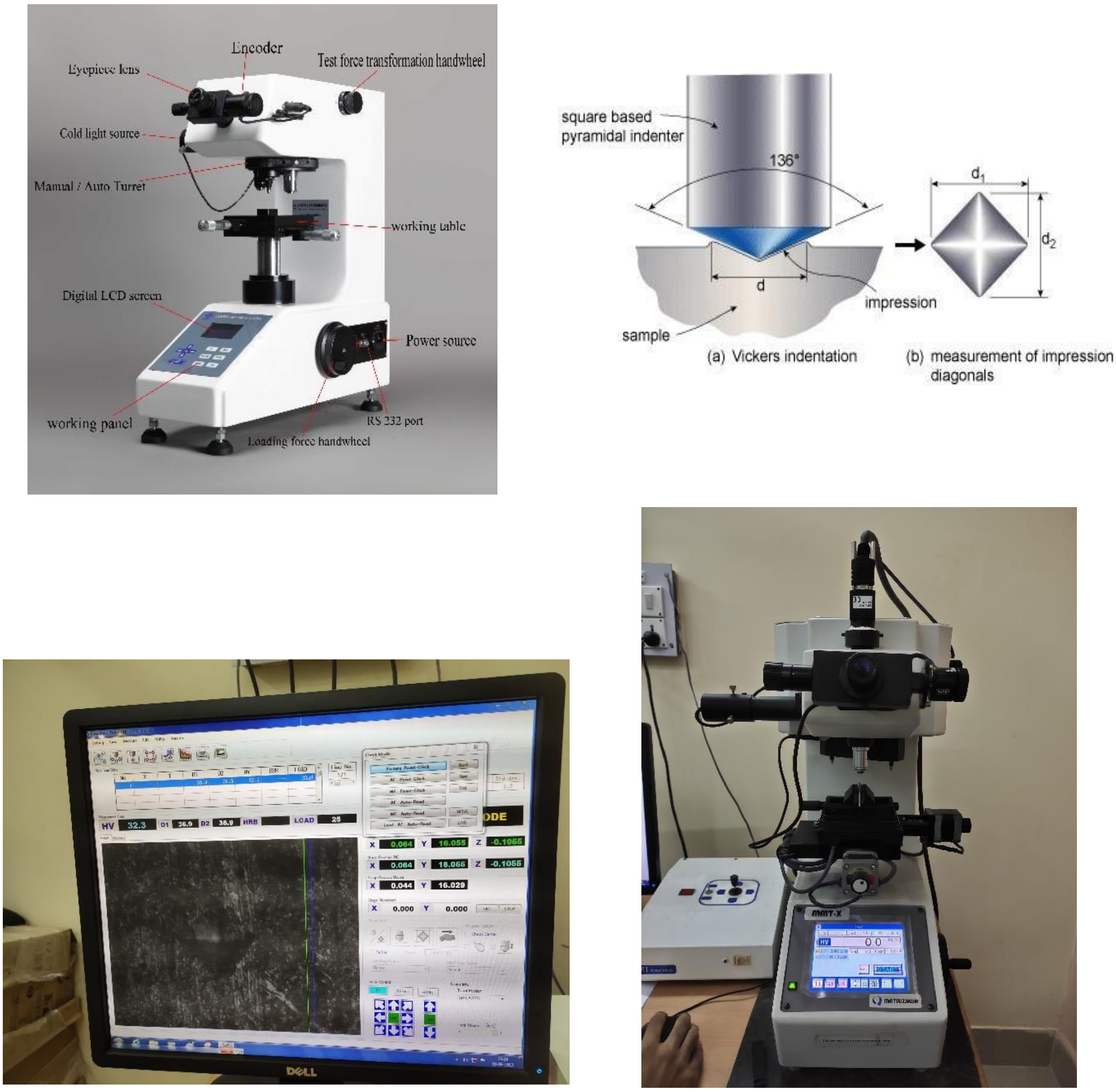


Figure 3.6 VMHT micro hardness tester

Microhardness testing was completed on all samples with the microhardness tester set at 1.33 kN load and 10 seconds of dwell time. Readings were taken from the fusion zone on each side of the weld at 5 mm spacing with two readings taken for each linear spacing.

Approximately 50 mm of readings were taken on each side of the weld zone from the fusion zone outward to determine values for the complete heat affected zone. 9 readings taken from the weld zone, for about 41 readings in total. This provided a clear understanding of the trend in hardness values across the weld pool, heat affected zone, and base material.

3.9 TENSILE TEST

Tensile testing is an important component of the characterization process as it provides critical information on the strength and ductility of materials under uniaxial tensile stresses, which is useful to compare different materials and designs. After confirming the geometry of the cut as well as operation parameters including material, thickness of the material, wire material/diameter, and number of passes (one in this case), the machine was zero-d on the side at the center of the weld bead. The geometry and operation were then executed with the speed and tension in the wire being observed to ensure optimization of parameters. The speed of the EDM cutting noticeably slowed down in the weld zone, as the filler material was less conductive than the base material due to secondary phase and nanophase around the aluminum matrix. Tensile bars were cut according to ASTM standard E8[51], which provides dimensions for plate-type and sheet-type samples. One of the simplest tests for determining mechanical properties of a material is the tensile test. In this test, a load is applied along the longitudinal axis of a test specimen. The applied load and the resulting elongation of the member are measured. Load-deformation data obtained from tensile and/or compressive tests do not give a direct indication of the material behavior, because they depend on the specimen geometry. Loads and deformations may be converted to stresses and strains.

Stress: $\sigma = \frac{F}{A^\circ}$;

Strains: $\epsilon = \frac{\Delta L}{L^\circ}$;

Elongation: $\delta = \frac{\Delta L}{L^\circ}$ *100%;

Modulus of elasticity: $E = \frac{\sigma}{\epsilon}$ or $E = \frac{F * L}{\Delta L * A^\circ}$

Where:

σ = normal stress on a plane perpendicular to the longitudinal axis of the specimen (MPa);

F = applied load (N);

A^o = original cross-sectional area (m^2);

ε = normal strain in the longitudinal direction (m/m);

δ = change in the specimen’s gage length (%);

L° = original gage length (m);

ΔL = length after tensile test (m);

E = Modulus of elasticity (GPa).

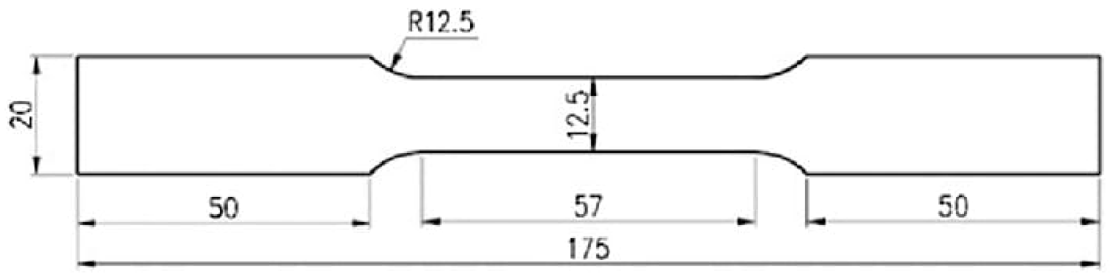


Figure 3.7 Schematic Tensile Specimen

Transverse tensile testing was done as per the ASTM E8-04 standard with a ram speed and strain rate of 2 mm/min and 1.3×10^{-3} s^{-1} respectively.

Sheet-type samples range in nominal thickness from 3m. Given the aluminum plates welded had a thickness of 3 mm, dimensions for sheet-type samples were used. Before testing, the samples were face milled to remove the protruded weld bead and form flat samples. To ensure the ultimate tensile strength of the material could be reached with the tester, an ultimate tensile strength of 125 MPa was assumed for the 6061-O welds. Using this value, as well as the 3 mm width along the center of the tensile bar, a thickness (T) of approximately 3 mm was calculated to stay within the limit of the tensile tester, which had an ultimate tensile testing capacity of up to 20 kN.

3.8 Figure a) Tensile specimen before test

3.8 Figure b) Tensile specimen after test

Joint efficiency is the ratio between tensile strength of welded joint and tensile strength of the unwelded parent metal. The joint efficiency of GMAW joints is approximately 49% and the joint efficiency of GTAW joints is 63%. Of the three types of welded joints, the joints fabricated by FSW exhibited a relatively higher joint efficiency (74%), and the joint efficiency is 34% higher compared to the GMAW joints and 15% higher compared to GTAW joints.

CHAPTER 4:

RESULTS AND DISCUSSIONS

Chapter 4: RESULTS AND DISCUSSIONS

VISUAL INSPECTION OF WELDS

The most popular way to determine the surface quality of a weld is via a visual inspection of the weldments. This kind of inspection, when carried out correctly, may often be a very efficient way to maintain acceptable welding quality and avoid welding problems. Figure 4.1 depicts the top view of AA6061 -welded joints using different welding processes. It can be remarked that for all the welded joints, the different welding processes successfully welded 3 mm thick AA6061 in butt joints. Moreover, it can be considered acceptable without any defects on the surface of the welded joints. Table 4.1 summarizes the result of the visual examination of the AA6061 butt joints welded using the two different welding techniques.
In the case of GMAW joints, the numerous high-speed droplets impinge on the weld pool, thereby a flattened weld pool occurs due to the higher arc pressure.

Figure 4.1 Top-view photo images of the welded joints.

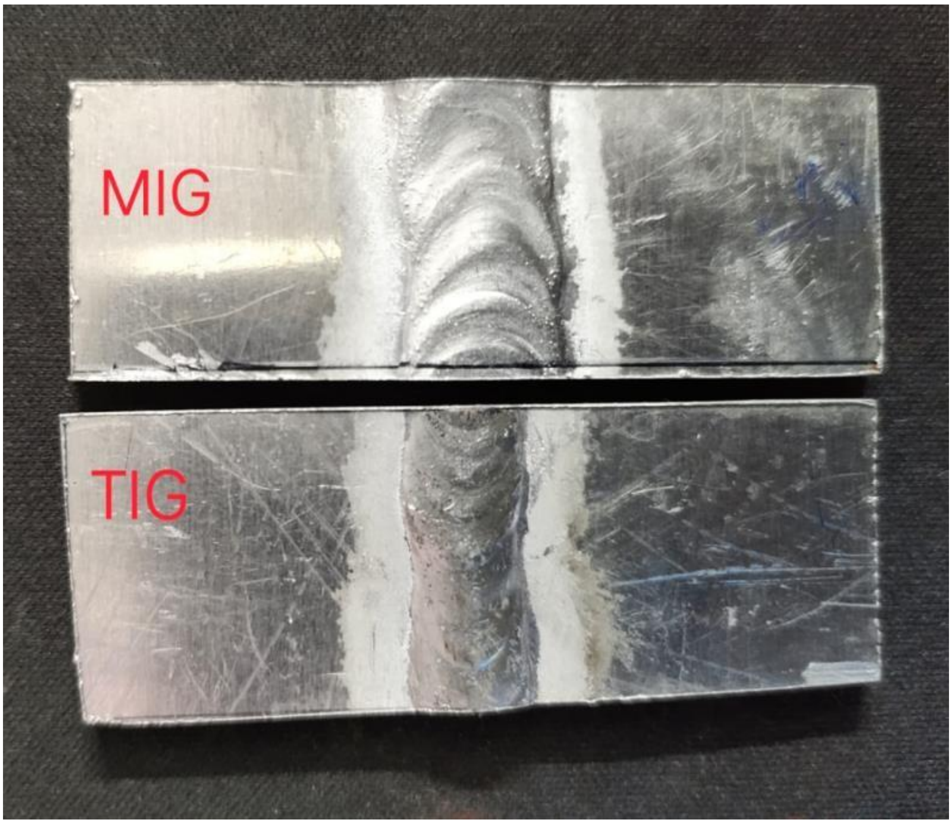


Table 4.1 Result of the visual examination:

	TIG	MIG
Appearance:	TIG weld on aluminum 6061 is very clean and smooth. The weld bead is narrower, and more uniform compared to MIG welding. There is a shiny appearance due to the precise control over the heat input and the absence of spatter.	MIG weld on aluminum 6061 is wider and less refined compared to TIG welds. There is spatter around the weld area. The weld bead has a slightly rougher texture.
Bead Profile:	The weld bead profile is more uniform with consistent width and height. The edges of the weld bead are smooth and blend seamlessly with the base metal.	The weld bead is wider and less consistent in width and height. The edges of the weld bead are not blend as seamlessly with the base metal as in TIG welding.
Defects:	TIG welds are less likely to have spatter. Porosity is rare but can occur if there is contamination or improper shielding gas flow. Cracks and undercutting are less common.	MIG welds are more prone to spatter. Porosity can be more common, especially if the shielding gas coverage is insufficient or the surface is contaminated. Other defects like lack of fusion or burn-through can occur if the parameters are not well controlled.
Heat Affected Zone (HAZ):	The HAZ is smaller because TIG welding allows for better control over the heat input. The transition between the weld and the base material is smooth.	The HAZ is larger because MIG welding uses a higher heat input. The transition between the weld and the base material is less smooth compared to TIG welding.

MACRO- AND MICROSTRUCTURAL ANALYSIS

The cross-sectional macrostructure of the welded joints is shown in Fig 4.2. From the macrographs, it can be seen that no macro-level defects were observed. The widths of the zones are varied for each welding condition.

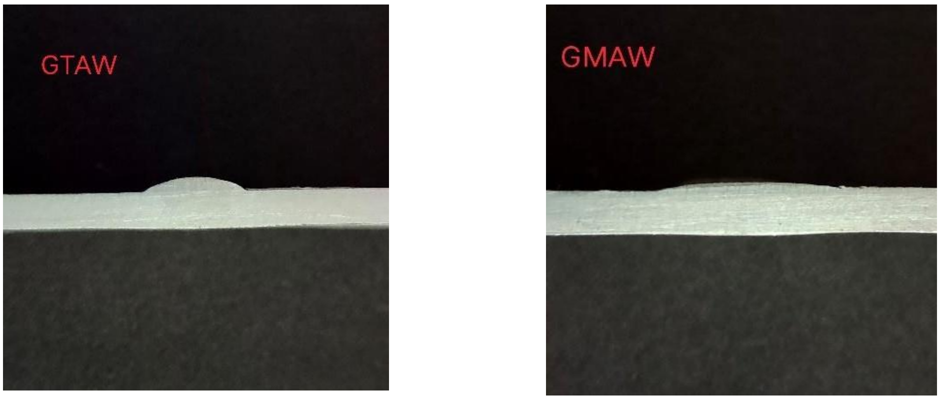
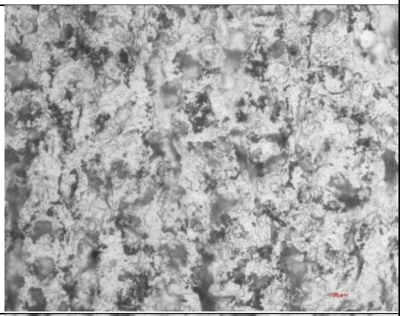
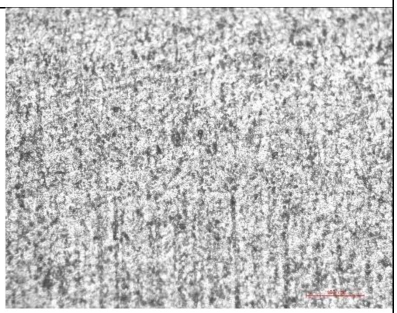
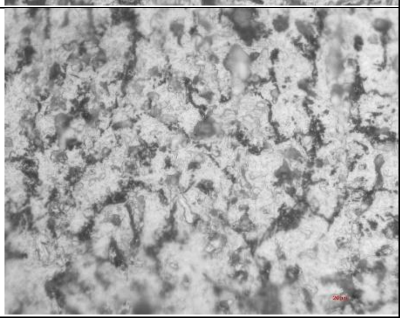
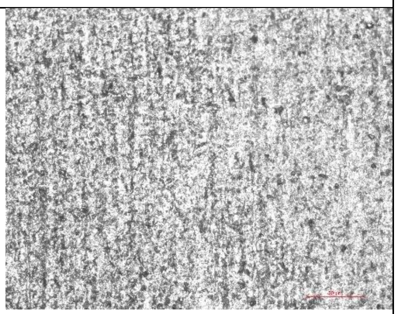
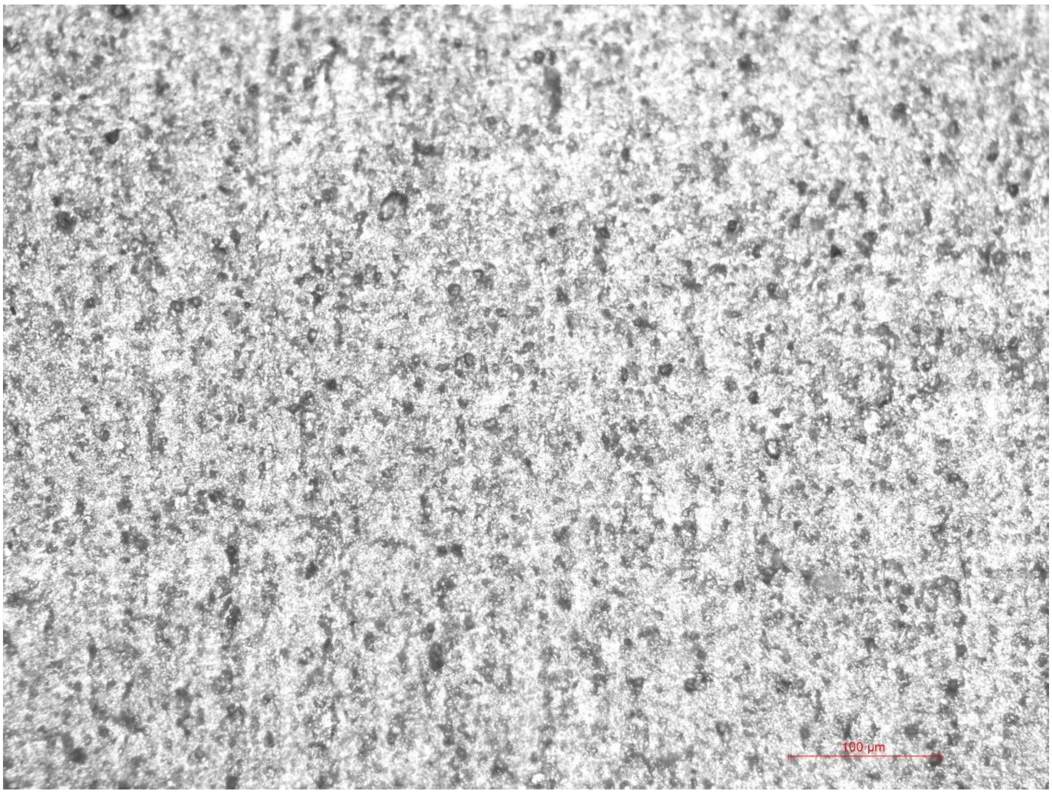


Figure 4.2 Macrographs of the welded joints

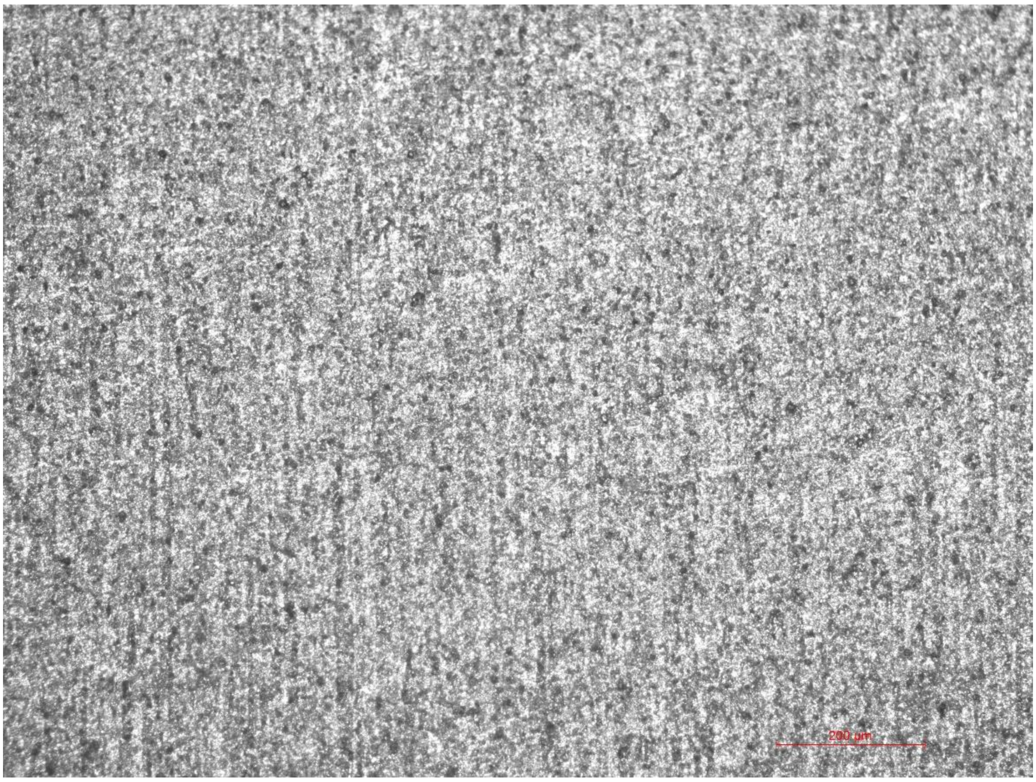
It is a difficult task to polish the aluminium alloy to give it a mirror-finish because it forms a very thin layer of oxide which protects it from further atmospheric oxidation. The cross-sectional surfaces of all the welded plates were properly polished by using all the necessary steps involving sandpaper finishing and rubbing against the high-speed polisher with fine abrasive particles. Fine-grained polishing papers (of grade 2800, 3000, and 3200) were used under study. The etchant of Keller's Reagent was prepared for application on the polished sur face of the samples. The etchant was applied for approximately 10 sec.

SPECIMEN	WELD ZONE 1000x	HAZ
GTAW		
GMAW		

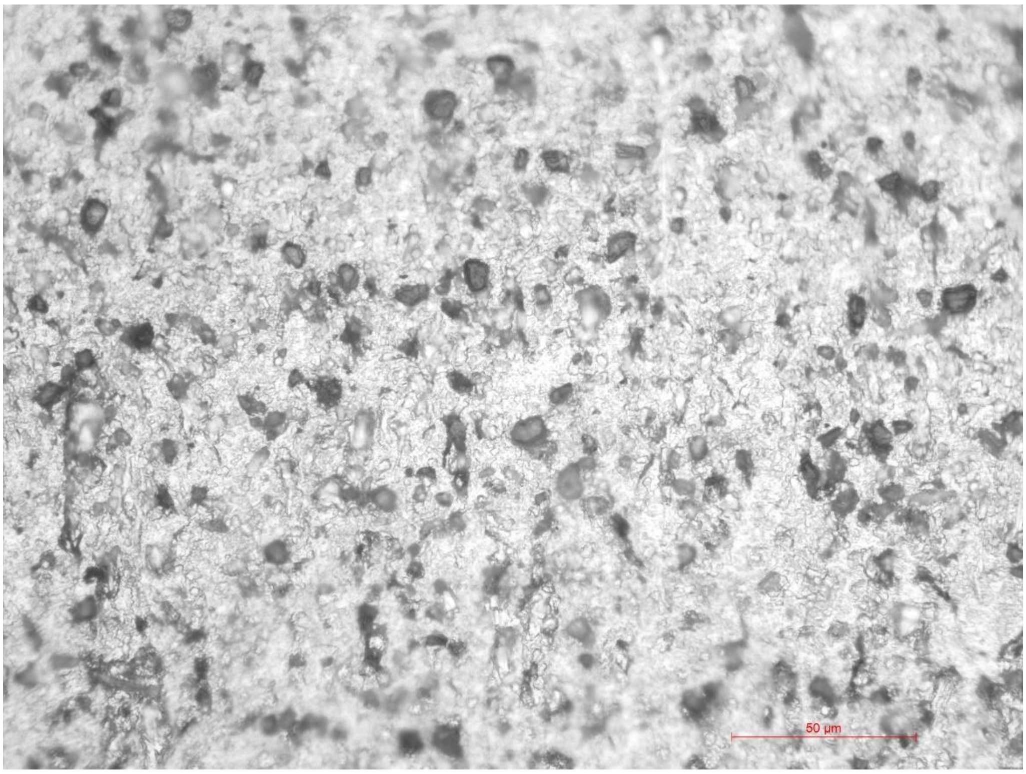
No defects such as tunnels or cracks were noted in all the investigated cross-sections of the welded joints using the two welding techniques. The welding features of WZ (weld zone) and HAZ (heat-affected zone) are typical for the fusion welding techniques (TIG and MIG).



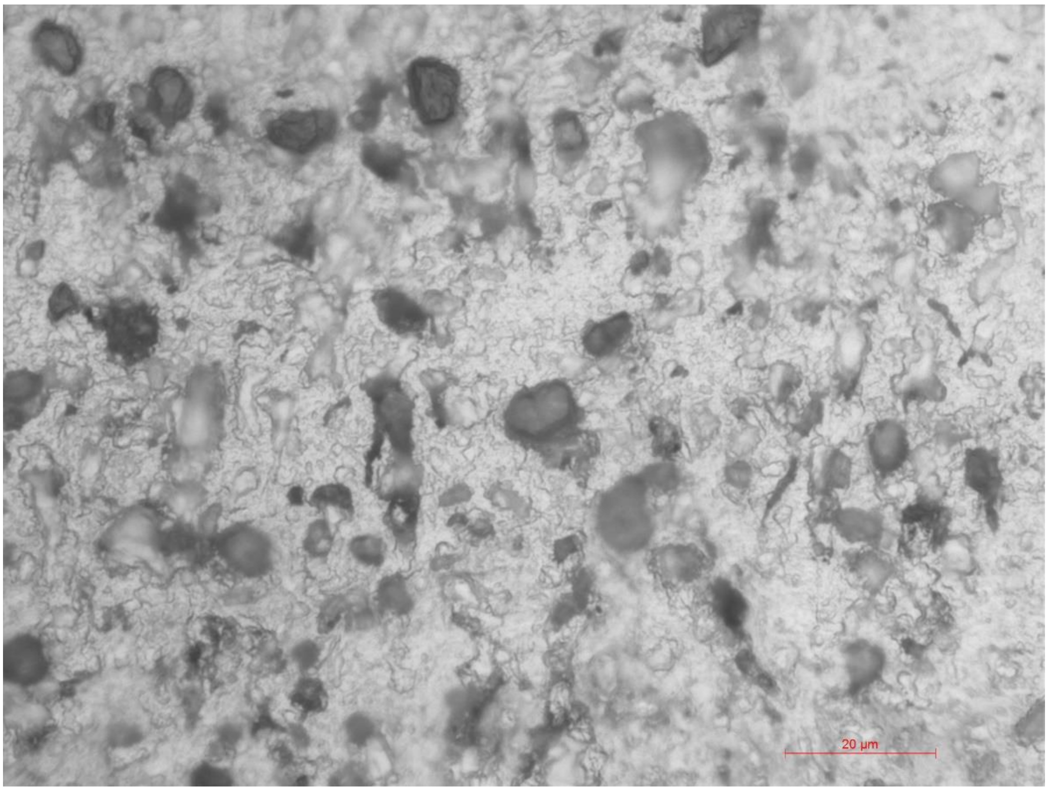
Base Matel 200x



Base Metal 100x



Base Metal 500x



Base Metal 1000x

It is clear from the microstructure that the widths of HAZ and PMZ are less for GTAW joint due to the less heat input involved in this process. The weld metal microstructure contains fine dendritic grains which are columnar in structure since the process is associated sufficient heat input and faster cooling rate.

The base material consists of an equiaxed and elongated grain structure with some hardened precipitates (i.e. β″ (Mg_5Si_6)) distributed along the grain boundary. This precipitate is thermodynamically unstable and sensitive to the heat input supplied by the welding process. Due to the transformation of β″ to β′ (Mg_9Si_5), there is a decrease in the mechanical properties mainly in the softening zone that lies exactly in the heat-affected zone (HAZ)

the weld metal (WM) is composed of columnar grain structures in an aluminium matrix.

The partially melted zone (PMZ) is the weakened region that forms next to the weld metal region in the fusion welded joints of 6061 aluminium alloy where the liquation can form partially when it is heated above the eutectic temperature because of the microsegregation of brittle eutectics (α (Al) + β (Mg_2Si)) along the grain boundary. This microsegregation of eutectics weakens the PMZ, and it may result in intergranular cracking owing to the tensile strains that form during welding. The PMZ is characterized by the equiaxed to columnar grain structure irrespective of the welding variants. When the peak temperature is increasing, the amount of micro-segregated eutectics increases and the concentration of solutionized Si in the α-phase decreases due to the high heat input generated by the GMAW process. It results in degrading the mechanical properties in the PMZ. It is visible from the micrograph that the widths of the HAZ and PMZ vary a lot with respect to the welding process. The width of these zones is lesser for GTAW joint compared GMAW joint. In the GMAW process, the solidification moves forward in the direction of the low temperature gradient which widens the widths of these zones compared to the other joints. This also results in the formation of columnar grains and causes the segregation of phases. In the GMAW process, the solidification moves forward in a certain direction, i.e. in the direction of the low temperature gradient, which in turn helps in the formation of columnar grains and causes the segregation of phases. During the GTAW process, the solidification moves back repeatedly which hampers the growth of columnar grains and therefore segregation is controlled. Due to the low heat input (0.229 kJ/mm) compared with GMAW joint, the distribution of phases is less in GTAW joints.

MICRO-HARDNESS TEST RESULT

The aluminum weld joint is heated by heat during the welding process, and then swiftly cooled. This change in the rate of heating and cooling affects the microstructure and mechanical properties of aluminum, and in turn changes the hardness of the weld area. The speed of cooling leads to the emergence of granules of different sizes. Smaller and more brittle microstructures, which can lead to reduced toughness. The specific hardness distribution of TIG weld and MIG weld depends on a few variables, such as welding parameters, the properties of the weld material, and the cooling rate of the weld metal. With these variables, it is very important to control these variables carefully to obtain the correct hardness and mechanical properties of the final product. The Vicker hardness tester device was utilized to determine the hardness of nine workpieces. Every single workpiece underwent a hardness test at seven predetermined locations: the center, the left and right sides of the HAZ, and the base metal zone. The distance between each indentation load was maintained at 4 mm.

Table 4.2: Hardness values at different location from center of weld

Location from center of weld to left and right (mm)	Hardness values for different welded sample					
	GMAW			**GTAW**		
	D1	**D2**	**HV**	**D1**	**D2**	**HV**
-16	31.1	31.8	**46.8**	31.1	31.7	**46.6**
-12	33.3	35.7	**39.3**	33.3	33.2	**41.1**
-8	33.7	35.3	**39.1**	33.8	35.7	**38.4**
-4	37.6	36.5	**33.7**	29.9	30	**51.8**
0	26.9	26.7	**64.4**	23.7	28.6	**67.9**
4	35.8	39.1	**33.1**	29.7	30.1	**52**
8	36.9	38.9	**32.3**	33.2	35.7	**39**
12	32.9	34.4	**42**	32.3	34.4	**41.7**
16	31.2	31.5	**46.1**	31.1	31.8	**46.8**

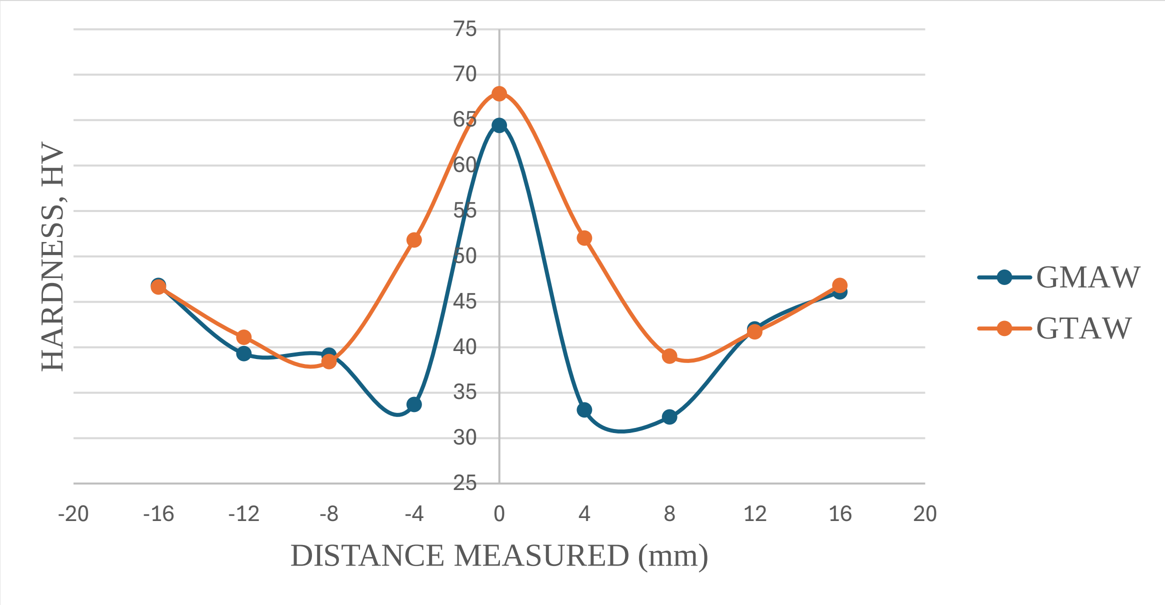


Figure 4.4 Microhardness measured across the cross section of the joint is plotted

The highest hardness was recorded in the WM region regard less of the variant used. The width of the softened zone varies with respect to the variant used. It can be clearly understood that these widths will vary based on the heat input that is generated by each of these processes. The GTAW joint recorded a higher hardness of 79 HV in the weld metal region. It can be observed that significant variation in the hardness across the various This is due to the low heat input (0.164 kJ/mm) with rapid solidification and the faster cooling rate associated with the process compared to regions was recorded. The base material (AA6061) is having a hardness value of 90 HV. A softened zone is formed evenly on both sides of the joint in the HAZ region irrespective of the weld variants. The hardness recorded in this zone will be ap proximately 60% of the base material hardness, where the exact failure of the specimen has taken place. These results are in good agreement with the tensile results where the exact location of the failure occurs. The weld metal is exhibiting the highest hardness compared to the HAZ in all the joints. WM records a slightly higher hardness compared with the HAZ region, even though the precipitates are completely dissolute in the WM zone. The reason behind the improvement in the WM zone is the enrichment of the solid solution with Mg and Si. The lowest hardness is recorded in the HAZ region which is slightly smaller than that of the WM region due to the vaporization or segregation of magnesium along the grain boundary in the HAZ region.

TENSILE TEST RESULT

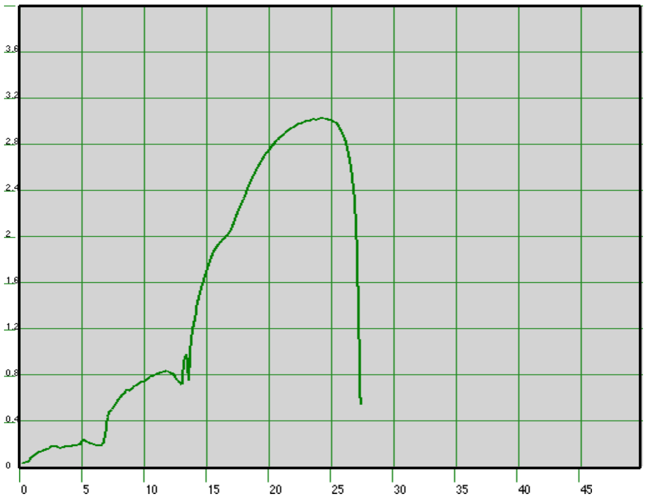
Sample ID	Tensile Project GTAW	Tensile Project GMAW
Test Type	tension-20kN	tension-20kN
Sample Type	Flat	Flat
Length(mm)	57	57
Thickness(mm)	2.99	3
Width(mm)	12.5	12.5
Sample Area (Sq mm)	37.34	37.54

Properties	GTAW	GMAW
Peak Load (kN)	3.031	2.97
Peak Stress (N/Sq mm)	81.178	79.121
Displacement at Peak Load (mm)	24.24	15.81
Strain at Peak Stress (%)	42.526	27.737
Yield Load (kN)	2.027	2.818
Yield Point Extension (mm)	16.74	14.16
Yield Stress (N/Sq.mm)	54.289	55.072

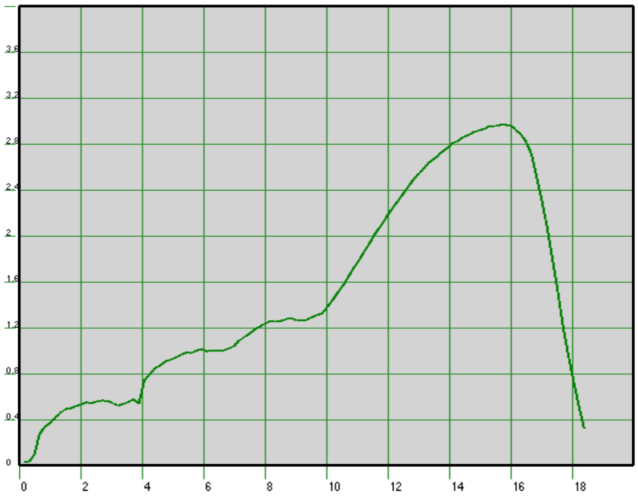
Table 4.3 Detail tensile test data

During tensile test plates welded with different types were tested. The data of force variation and plate displacements were received in Excel files. Charts representing results and calculations are shown and compared below. Function: $F=f(\Delta l)$.

Force(kN) Vs Elongation(mm)

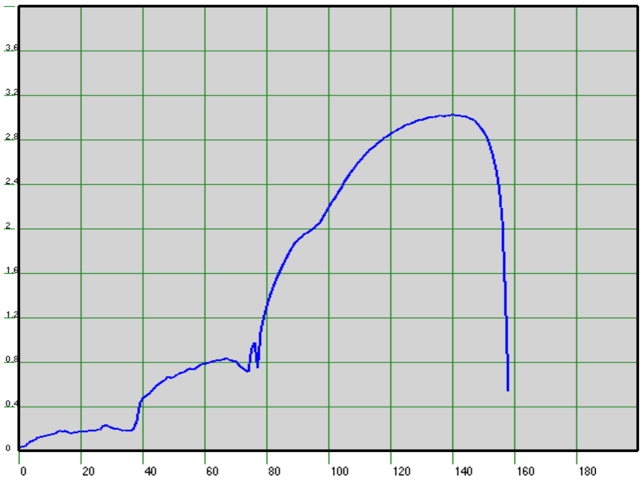


a) For the GTAW plate

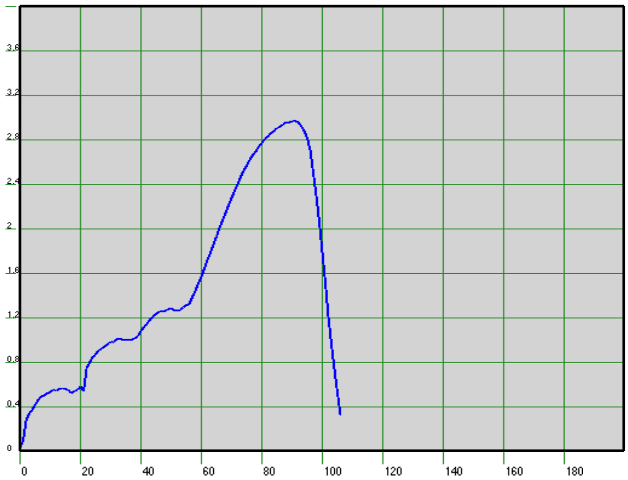


b) For the GMAW plate

Force (kN) Vs Time (Sec)

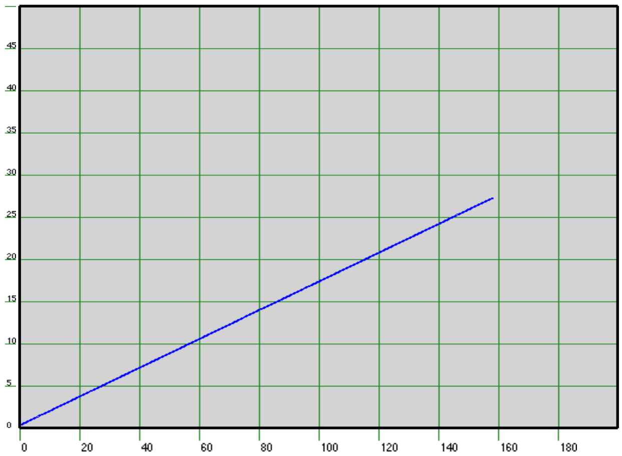


c) For the GTAW plate

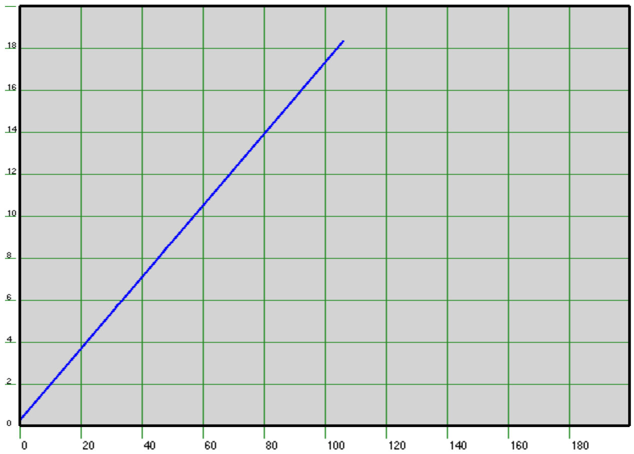


d) For the GMAW plate

Elongation (mm) Vs Time (Sec)

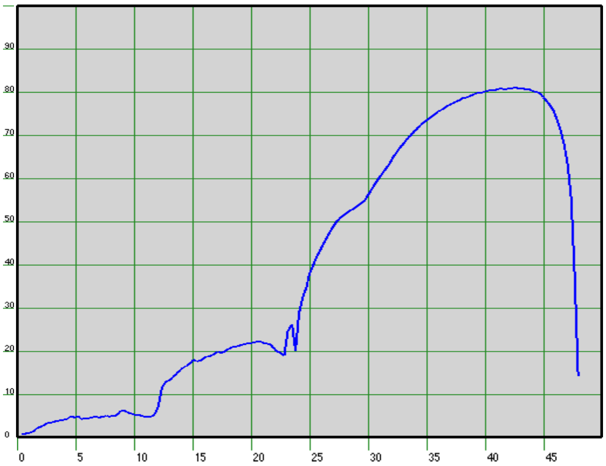


e) For the GTAW plate

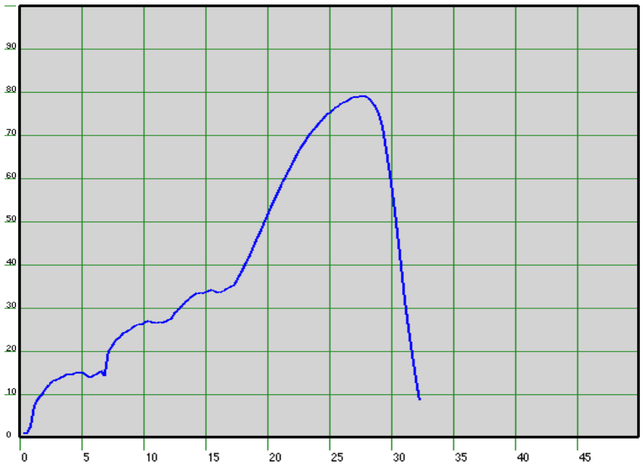


f) For the GMAW plate

Stress (N/Sq mm) Vs Strain (%)



g) For the GTAW plate



h) For the GMAW plate

Table 4.4 Tensile properties of the welded joints

Joint type	yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation in 57-mm gauge length (%)	Reduction in c.s.a. (%)	Joint efficiency (%)	Fracture location
GMAW	55.072	79.121	32.56	8.26	61.30	HAZ
GTAW	54.289	81.178	37.08	5.80	74.25	HAZ

The transverse tensile properties such as yield strength, tensile strength, percentage of elongation alloy joints were evaluated. The yield strength and tensile strength of unwelded parent metal are 55 MPa and 125 MPa, respectively. However, the yield strength and tensile strength of GMAW joint is 55.072 Mpa and 79.121 Mpa respectively. This indicates that there is a 37 % reduction in strength values due to GMAW welding. Similarly, the yield strength and tensile strength of GTAW joint is 54.289 Mpa and 81.178 Mpa, respectively which are 32% lower compared to parent metal. The maximum tensile strength of 81.178 MPa was achieved for the joint made with the GTAW. This is due to the formation of finer dendritic grains in the WM zone which enhances the tensile strength of the joint. In contrast, the lowest tensile strength of 79.12 MPa was achieved for the joint made with the GMAW.

The coarser grain structure with the partial dissolution or coarsening of harder precipitate in the HAZ is the reason for the failure of the specimen in the HAZ region. It is observed from the fracture surface that both the joints have failed in the HAZ region which indicates softening has occurred in this region. It suggests that the fracture of the joint might be in the HAZ region where the softened zone forms. This softened zone usually occurred in the HAZ region due to the coarsening of harder precipitate when an alloy is subjected to higher peak temperatures. This lowest hardness in the softened zone may be because of the partial dissolution or coarsening of harder precipitate which is a hardened and unstable precipitate. The fracture surface of GMAW joints shows less area distribution of dimples with large size compared to the other joints. This is due to the high heat input (0.242 kJ/mm) of GMAW joints. This indirectly leads to the inferior mechanical properties (i.e. tensile and hardness) of the GMAW joints.

CHAPTER 5:

CONCLUSION

5. CONCLUSION

Al-6061 possesses good weldability under both types of welding conditions i.e., solid state and liquid state. In this work, an attempt has been made to compare and analyze the mechanical properties and microstructural changes in Al-6061 plates after two different welding- MIG and TIG. These two welding are commonly applied in Al-alloys. As per the results obtained by tensile, hardness, fractography and microstructural tests, through an extensive analysis of welding parameters, mechanical testing, and microstructural examination, the following key conclusions have been drawn:

- The TIGW sheet, in which filler was used, has shown the highest values of UTS (231 MPa) and YS (192 MPa) with 9.67 % of elongation. MIGW sheet has shown UTS of 195 MPa which is 15% lower than that of TIGW sample. TIG welded joints exhibit higher 0.2% yield strength, ultimate tensile strength, and elongation, indicating better performance under mechanical stress. The finer microstructure achieved through TIG welding contributes to these enhanced properties. Both the arc welded joints have shown a ductile behavior of the fracture by possessing a considerable plastic flow.
- As per the microstructural observation, the fine solid grain boundaries of primary phase in BM get converted into thick dendrites in WZ. Also, the coarse secondary phase (black) of BM has changed into fine particles in the WZ.
- The microhardness values for TIG welded joints are typically higher than those for MIG welded joints. This is attributed to the concentrated heat input and faster cooling rates in TIG welding, which produce a finer grain structure and reduce the presence of defects and inclusions.
- Hardness results establish that WZ of TIGW sample is significantly higher by 17% MIGW samples respectively. The HAZs in MIGW sample have been reported as less hard than other zones of the plates whereas, in TIGW sample, the accumulation of secondary phase has made the HAZ comparatively harder than BM and WZ. The HAZ in TIG welded joints is narrower than that in MIG welded joints. This narrower HAZ helps preserve more of the base metal's original properties, reducing the likelihood of weakening the joint and contributing to the higher mechanical properties observed in TIG welds.

FUTURE SCOPE

The comparative study of aluminum 6061 welded joints using TIG and MIG welding techniques has opened several avenues for further research and development. Future work in this field can enhance the understanding of welding processes, improve mechanical properties, and broaden the applications of aluminum 6061 in various industries. The following are key areas for future research:

1. Conduct detailed microstructural analysis using advanced techniques like electron backscatter diffraction (EBSD) and transmission electron microscopy (TEM) to understand the grain structure and phase transformations in greater detail.
2. Study the effects of various welding parameters on the precipitation hardening process in aluminum 6061 to optimize the distribution and size of precipitates, thereby enhancing mechanical properties.
3. Investigate the effects of different post-weld heat treatments on the mechanical properties and microstructure of welded joints. This includes exploring various annealing and aging treatments to achieve optimal strength and ductility.

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