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A Review on GTAW Technique for High Strength Aluminium Alloys (AA 7xxx series)

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ABSTRACT

Gas tungsten arc welding (GTAW) is an important joining technique for high strength aluminium alloys with their increasing applications in aerospace, aircraft, automotive, aviation space shuttle, rocket propulsion for missiles automotive industries, marine engine components. External throw away tanks for military aircrafts and other industries. In this document the research and progress in GTAW of high strength aluminium alloys especially AA 7xxx series are critically reviewed from different perspectives. Gas tungsten arc welding have been used to investigate the Weldability of high strength aluminium alloys. Some important GTAW process parameters and their effects on weld quality are discussed. Mechanical properties of welds such as tensile strength, hardness, and other important structural properties are discussed. The aim of the report is to review the recent progress in GTAW of high strength aluminium alloys (AA 7xxx series) and to provide a basis for follow-on research.

Keywords: *GTAW; Process parameters; high strength aluminium alloys (AA 7xxx series); Mechanical property.*

1. INTRODUCTION

Aluminum is the most abundant metal available in the earth's crust. Steel was the most used metal in 19th century but Aluminium has become a strong competitor for steel in engineering applications. Aluminium has many attractive properties compared to steel, it is economical and versatile to use, that is the reason it is very widely used in the aerospace, automobile and other industries. Aluminium alloys have very low density; compared to steel it has almost one thirds the density of steel. Properly treated alloys of aluminum can resist the oxidation process which steel cannot resist; it can also resist corrosion by water, salt and other factors [1].

Aluminum alloys can be separated into two major categories: Non heat-treatable and heat-treatable. The initial strength of non heat-treatable alloys depends primarily upon the hardening effect of alloying elements such as silicon, iron, manganese and magnesium. The non heat-treatable alloys are mainly found in 1xxx, 3xxx, and 4xxx and 5xxx series. Additional strength is usually achieved by solid-solution strengthening or strain hardening. The initial strength of heat-treatable alloys depends upon the alloy composition, just as the non heat-treatable alloys. In order to improve their mechanical properties they need to undergo solution heat treating and quenching followed by either natural or artificial aging (precipitation hardening). This treatment involves holding the work piece at an elevated temperature and followed by controlled cooling in order to achieve maximum hardening. The heat-treatable alloys are found primarily in the 2xxx, 6xxx and 7xxx alloy series [1].

The 7xxx series alloys contain zinc in amounts between 4 and 8 % and magnesium in amounts between 1 and 3 %. Both have high solid solubility in aluminum. The addition of magnesium produces a marked increase in precipitation hardening characteristics. Copper additions between 1 and 2 % increase the strength by solid solution hardening, and form the basis of high strength aircraft alloys. The addition of chromium, typically up to 0.3 %, improves stress corrosion cracking resistance. The 7xxx series alloys are used predominantly in aerospace applications, 7075-T6 being the principal high strength aircraft alloy [1].

Aluminium alloys can be joined by most fusion and solid-state welding processes as well as by brazing and soldering, but inert gas tungsten arc welding (GTAW or TIG) and inert gas metal arc welding (GMAW or MIG) are the two most commonly used welding processes. The welding of aluminum alloys is always represented as great challenge for designers and technologists. As a matter of fact, many difficulties are associated to this kind of joining process, mainly related to the presence of a tenacious oxide layer, high thermal conductivity, and high coefficient of thermal expansion, solidification shrinkage, improper microstructure due to filler material, and above all high solubility of Hydrogen and other gases, in a molten state. A literature review has been done to study important GTAW processing parameters and their effects on weld quality.

1.1. Conventional fusion welding methods for Aluminum alloys.

There are many different types of conventional welding. These include oxyacetylene welding, shielded metal arc welding, gas-tungsten arc welding, plasma arc welding, gas-metal arc welding, flux-core arc welding, submerged arc welding, electroslag welding, electron beam welding, and resistance spot welding. Of these techniques the most popular are oxyacetylene welding (OAW), gas-tungsten arc welding (GTAW), and gas-metal arc welding (GMAW). GTAW is a process that melts and joins metals by heating them with an arc established between a non-consumable tungsten electrode and the metals. These welding processes use inert gases such as argon and helium to provide shielding of the arc and the molten weld pool. This is why GTAW and GMAW are also called tungsten-inert gas (TIG) and metal-inert gas (MIG) welding processes, respectively. The conventional welding techniques are usually desirable due to their simplicity, low cost, portability and are generally used in maintenance, repair and field construction sites [2].

1.2. GTAW applications.

The greatest advantage of the GTAW process is that it will weld most metals and metal alloys than any other arc welding process. TIG can be used to weld many aluminum alloys, magnesium alloys, copper alloys, brass, bronze, steels including stainless steel, nickel alloys such as Monel and Inconel, titanium, GTAW can also weld dissimilar metals to one another such as copper to brass and stainless to mild steel.

1.3. GTAW Process parameters and its effects.

The gas tungsten arc welding (GTAW) process originally was created in the 1940s to weld magnesium and aluminum alloys for aircraft applications. It was developed because a welding method was needed that performed better on these materials than did shielded metal arc welding (SMAW). Today, many precision parts are gas tungsten arc welded, including batteries, metal bellows, pacemakers, medical components, and surgical tools [4].

Originally, helium was used as the shielding gas, and the process became known as heliarc welding. Argon gas soon became the most widely used shield gas because of its lower cost and smoother arc. In the GTAW process, an electrical arc is established between a tungsten electrode and the part to be welded. To start the arc, a high voltage is used to break down the insulating gas between the electrode and the part. Current is then transferred through the electrode to create an electrode arc. The metal to be welded is melted by the intense heat of the arc and fuses together either with or without a filler material. The arc zone is filled with an inert gas to protect the tungsten electrode and molten material from oxidation and to provide a conducting path for the arc current. Shield gases used are argon, helium, mixtures, of argon and helium, or small percentages of hydrogen mixed with argon. The shield gas usually is chosen according to the material to be welded [5]. A typical welding system usually consists of the following elements: Welding power supply. Weld controller, Welding torch, and Tungsten electrode. Besides the equipment, one of the most important aspects of the GTAW process is welding parameters used. A weld program consists of a list of welding parameters developed to achieve a specific weld quality and production output. A change in any parameter will have an effect on the final weld quality, so the welding variables normally are written down or stored in the welding equipment memory [5]. For welding in many precision or high-purity applications, a specification may already be written that outlines the recommended welding parameters, including the base material; part diameter(s); weld joint and part fit-up requirements; shield gas type and purity; arc length; and tungsten electrode material, tip geometry, and surface condition [4]. Some welding equipment suppliers offer a series of pre calculated weld programs for a variety of part diameters, materials, and thicknesses. Welders should always follow an equipment supplier's suggested procedures first because the suppliers usually have performed a significant amount of qualifying and troubleshooting work [4]. As per the previous experimentation following are the different weld parameter that mainly determines quality of the weld.

a. Current. b. Frequency. c. Voltage. d. Arc length.
e. Welding gun speed. f. Welding gun position.
g. Shielding gas. h. Heat input.

1.3.1. Current.

Current has direct influence on weld bead shape, welding speed and quality of the weld. Most GTAW welds employ direct current on electrode negative (DCEN) (straight polarity) because it produces higher weld penetration depth and higher travel speed than on electrode positive (DCEP) (reverse polarity). Besides, reverse polarity produces rapid heating and degradation of the electrode tip, because anode is more heated than cathode in gas tungsten electric arc [6]. Reverse polarity may be of interest in welding aluminum alloys because of the cathodic cleaning action of negative pole in the work-piece, that is the removal of the refractory aluminum oxide layer. However alternating current is better adapted to welding of aluminum and magnesium alloys, because it allows balancing electrode heating and work-piece cleaning effects. Weld penetration depth obtained with AC is between depth obtained with DCEN and DCEP, as illustrated in Figure 1.

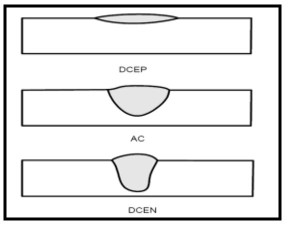

Fig.1. Effect of current &polarity on weld bead.

When using alternating current sine waves for welding, the terms electrode positive and electrode negative which were applied to the work piece and electrode loose their significance. There is no control over the half cycles and you have to use what the power source provides. The current is now alternating or changing its direction of flow at a predetermined set frequency and with no control over time or independent amplitude. During a complete cycle of alternating current, there is theoretically one half cycle of electrode negative and one half cycle of electrode positive. Therefore, during a cycle there is a time when the work is positive and the electrode is negative. And there's a time when the work is negative and the electrode is positive [5].The TIG current range for different metal thickness as shown in Fig.2.

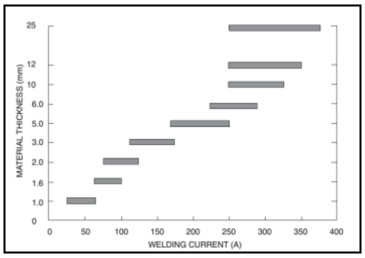

Fig.2.TIG current ranges for various material thicknesses.

In contrast to constant current welding, in pulsed current gas tungsten arc welding, heat energy is supplied only during peak current pulses, allowing it to dissipate into the base metal during the background current and thus lowering heat buildup in the adjacent base material, thus leading to a narrower heat affected zone. Pulse frequency had a significant positive effect on most of the important bead parameters [7].

The pulsed current welding technique records lower peak temperatures and lower magnitude of residual stresses compared with constant current welding, which is highly preferable for thin sheet welding. The gas tungsten arc welded aluminium alloy joint fabricated by pulsed current welding technique exhibits superior tensile properties compared with constant current welding technique. The formation of finer grains caused by pulsed current is the main reason for enhanced tensile and hardness properties of the joints [8].

AA7075 aluminium alloy joints fabricated by PCGTAW exhibited very high strength and the enhancement in strength is approximately 25% compared to CCGMAW joints; 15% compared to PCGMAW joints and 8% compared to CCGTAW joints. An additional enhancement of 8–10% in strength has been obtained due to simple post weld aging treatment irrespective of welding techniques. As welded PCGTAW joints exhibited relatively higher joint efficiency (56%) and the improvement in joint efficiency is 25% compared to CCGMAW joints; 16% compared to PCGMAW joints and 8% compared to CCGTAW joints. The maximum joint efficiency of 60% has been attained in post weld aged PCGTAW joints, which is 4% higher than the as welded PCGTAW joints. Hardness is lower in weld metal (WM) region compared to PMZ, HAZ and BM regions irrespective of welding technique. Very low hardness is recorded in CCGMAW joints (70 VHN) and the maximum hardness is recorded in PCGTAW joints (100 VHN). The simple aging treatment applied to the joints increased the weld metal hardness irrespective of welding processes and the increase in hardness is 15–20% [12]. PCGTAW technique produced very fine grains in the weld metal region compared to all other techniques and the reduction in grain diameter is 75% compared to CCGMAW joints; 66% compared to PCGMAW joints; 50% compared to CCGTAW joints. There is no appreciable change in grain diameter due to post weld aging treatment. The simple aging treatment applied to the joints caused appreciable changes in the formation of precipitates and their distribution. Relatively higher amount of precipitates are seen in post weld aged (PWA) joints compared to as welded (AW) joints [9].

Current pulsing has been used by few investigators to obtain grain refinement in weld fusion zones and improvement in weld mechanical properties.

Significant refinement of the solidification structure has been reported in aluminum alloys and titanium alloys. Most of the reported literatures are focused on effect of pulsed current welding on grain refinement in fusion zone microstructure and tensile properties. Pulsed current welding is found to be beneficial to enhance the fatigue resistance of the GMAW and GTAW joints and fatigue performance of pulsed current welded joints are superior compared to the continuous current welded joints. [10].

1.3.2. Frequency.

Alternating current makes constant reversals in direction of current flow. One complete reversal is termed a cycle and is referred to as its frequency. As stated, in the United States the frequency of its delivery is 60 cycles per second, or to use the preferred term 60Hz. This means there are 120 reversals of current flow direction through the arc per second. The faster the current going through the arc changes direction, increases the arc pressure making the arc more stable and directional. When normal 60 Hz arc compared with 180 Hz arc, it is found that current is changing direction 3 times faster than normal with a narrower arc cone and a stiffer more directional arc. The arc does not deflect but goes directly to where the electrode is pointed. This concentrates the arc in a smaller area and results in deeper penetration [6]. Pulsed DC current with low-frequency (1-10 Hz) is being used to reduce weld distortion, to improve tolerance to joint preparation and to cast-to-cast variations. Current magnitude and duration of the pulses are determined by material family and thickness of the component to be welded. This current is used in welding of stainless steels. High-frequency pulsed current (5-30 kHz) improves arc stiffness, increasing penetration depth and maximum welding speed and decreasing formation of porosity in the weld metal. This current is advantageous in automatic welding applications [6].

1.3.3 Voltage.

Voltage is the amount of pressure induced in the circuit to produce current flow measured in voltage. And it is the unit of pressure or electromotive force that pushes current, or electrons, through a circuit. One volt will push one ampere through a resistance of one ohm. Welding voltages typically range from 14 to 35 volts [11].

1.3.4 Arc length.

Conceptually, a welding arc can be thought of as a conversion device that changes electrical energy into heat. The amount of heat that an arc produces from electricity depends upon many factors. One of the most important is arc current. When the arc current is increased, the amount of heat the arc produces is increased; the reverse is also true. Another factor which controls arc heat is arc length [11]. The arc length is the distance between the electrode tip and the work-piece. The arc length in GTAW is usually from 2 to 5 mm [6]. Changes in the length of an arc will cause changes in the amount of heat available from the arc. Consequently, successful welding depends upon control of both the arc current and arc length. Most of the time when considering manual welding the arc current is controlled by the welding power supply and the arc length is controlled by the welder [11].

A welding arc has been defined as "A controlled electrical discharge between the electrode and the workpiece that is formed and sustained by the establishment of gaseous conductive medium, called arc plasma." An arc, or electrical flame, emits bright light, as well as ultraviolet and infrared radiation. Depending on the current level, arc temperatures may be very high, relative to the base metal melting point, producing enough heat to melt any known material. The characteristics of the arc depend on the shielding gas present in the arc environment because it affects the anode, cathode, and plasma regions found there [11]. Arc plasma is "A gas that has been heated by an electric arc to at least a partially ionized condition, enabling it to conduct an electric current." It is the visible electrical flame, or arc, in the gap between the anode and cathode. The arc voltage is the sum of the anode and cathode voltages plus the voltage across the arc plasma. With most welding processes, this voltage increases when the electrode and work piece move farther apart and decreases as they move closer together. Arc voltage is also impacted by the electrical conductivity of the shielding gas selected [11].If the arc length increases, the voltage to maintain the arc stability must increase, but the heat input to work-piece decreases due to radiation losses from the column of the arc. Consequently, weld penetration and cross section area of melted material decrease with increasing arc length [6].

One problem peculiar to the 7XXX series is that the zinc rapidly forms an oxide during welding, affecting the surface tension of the weld pool and increasing the risk of lack of fusion defects. This requires the use of welding procedures in which the welding current is some 10–15% higher than would be used for a 5XXX alloy. It has also been found to be beneficial to use a shorter arc than normal so that metal transfer is almost in the globular range [3].

1.3.5 Welding gun speed.

The effect of increasing the welding speed for the same current and voltage is to reduce the heat input. The welding speed does not influence the electromagnetic force and the arc pressure because they are dependent on the current. The weld speed increase produces a decrease in the weld cross section area, and consequently penetration depth (*D*) and weld width (*W*) also decrease, but the D/W ratio has a weak dependence on travel speed. These results suggest that the travel speed does not influence the mechanisms involved in the weld pool formation, it only influences the volume of melted material. Normal welding speeds are from 100 to 500 mm/min depending on current, material type and plate thickness [6].

In TIG welding of aluminum alloy AA6351, the depth of penetration of weld bead decreases with increase in bevel height of V butt joint. Maximum Tensile strength of 230 Mpa was observed at weld speed of 0.6 cm/sec and tensile strength is higher with lower weld speed. This indicates that lower range of weld speed is suitable for achieving maximum tensile strength. Bevel angle of the weld joint has profound effect on the tensile strength of weldment**.** Bevel angles between 30^0 to 45^0 are suitable for maximum strength. The heat affected zone, strength increased with decreasing heat input rate [14].

1.3.6 Welding gun position.

The non-consumable electrode angle influences the weld penetration depth and the weld shape. Electrode angles between 30º and 120º are used. Small angles increase arc pressure and penetration depth but have high tip shape deterioration. Electrode angles from 60º to 120º maintain tip shape for longer periods and give welds with adequate penetration depth-to-width ratio [6].

1.3.7 Shielding gas.

Argon is used in welding of carbon and stainless steels and low thickness aluminum alloys components. For welding thick aluminum work-pieces and other high-conductive materials, such as copper alloys, helium is recommended because it has higher ionization potential than argon, needing higher voltage for arc initiation and maintenance, but producing higher heat-input. Helium or helium/argon (30-80% He) mixtures allow increased welding speed and improved process tolerance. Mixtures of argon with up to 5% of hydrogen are frequently used in welding of austenitic stainless steels. Hydrogen increases arc-voltage and consequently heat input, increasing weld penetration and weld travel speed, as well improving weld appearance. Argon/hydrogen mixtures are also used in welding of copper nickel alloys. Argon is also used as back side shielding gas, mainly in welding of stainless steels, aluminum alloys and reactive metals. Flow rates of shielding gases depend on weld thickness, being 4-10 l/min for argon and 10-15 l/min for helium, because it is lighter than argon, and consequently less effective in shielding. Gases with a purity of 99.995% are used in welding most of the metals, though reactive materials such as titanium need contaminant level less than 50 ppm [6]. The gas flow must not be too high in order to allow a good shielding effect both on the weld pool and on the solidifying material. This result is also very important in terms of manufacturing costs: a low gas flow rate helps minimizing the expenses for helium which is probably the most expensive among inert gases. The inclination of the gas flow into the chamber should be perfectly horizontal or equal to at least 30^0 in order to guarantee good shielding results. The height of the isolation chamber must be quite short. This situation guarantees an optimum distribution of helium inside the chamber itself, both near the keyhole and far from it [12].

Pulse current, base current, pulse duty cycle, frequency and percentage of Helium in Argon plays significant role on microstructure and mechanical properties of welded Al alloy, but pulse current plays the maximum role *i.e.* 29.31%. In this investigation, pulse current of 165 A, background current of 135 A, pulse frequency of 125 Hz, pulse duty cycle of 45% and 30% of Helium with Argon affects the maximum to the mechanical properties [13].

The experimental and a numerical research to find an interrelationship between alternate supply of shielding gas and weld quality in a GTA welding process has been carried out to check out the welding characteristics according to the variation of alternate supply of shielding gas. A two-dimensional axisymmetric heat and fluid mathematical models for a welding arc and weld pool was developed to verify the effect of alternate supply of shielding gas. The computed results showed that the range of molten metal at the top of weld pool for supply of He shielding gas became wider than that for supply of Ar shielding gas. However, the arc pressure of supply of Ar shielding gas was higher than that of He shielding gas about three times. The comparison between the calculated and measured results has been performed in order to verify the developed mathematical models. The calculated bead width and bead penetration are in good agreement with the experimental results with about 5% relative error. These results showed that the developed computational models are very adequate to predict in the weld pool and bead geometry. It is also found that the effect of alternate supply of shielding gas should be useful to apply for a narrow -gap welding process [14].

1.3.8 Heat input.

Energy supplied by welding heat sources must satisfy a number of requirements. It is necessary to heat the edges of pieces being joined to a temperature exceeding the melting points of the materials and to provide penetration of the molten zone deep enough into the materials, so as to produce a strong joint of permanent nature with minimum overheating of the surrounding materials. In fusion welding processes heat is supplied by the arc or by suitable heat and this heat is utilized to melt the electrode and a filler material and some portion of the parts to be welded. Ultimately the liquid after solidification forms the solid bond to unite the two parts. Heat is carried away from the welded zone by conduction and as a result the temperature at a point in the weldment rises to a peak value, and then cools to room temperature as the weld material looses heat to surrounding continuously. A plot of this continuous change in temperature with time is known as thermal profile. The thermal profile in the region near the weld have a significant impact for the formation of weld metal and heat affected zone(HAZ), its microstructure and mechanical properties and joint strength. Cooling rates are closely related to joint thermal profiles and they directly influence the residual stresses developed in the joint. It is therefore necessary to understand the mechanism of heat generation, its transfer to the welding plate and its transmission through the weldment [15].

In fusion welding processes the heat is supplied by suitable heat source and this heat is utilized to melt the electrode and /or filler metal and some portion of the parts to be welded. The heat generated by the source gets distributed in the following manner: To the electrode and the work piece by thermal conduction and the surrounding atmosphere by convection and radiation. Initially the source heat is concentrated in the portion of work piece immediately under the arc; there after it spreads throughout the weldment due to conduction. This conductional heat along with the heat coming directly from the heat source causes increase of temperature of any point in the weldment. The nature of temperature change at a particular point depends on the position of the points with respect to heat source, thermal properties of the metal and environmental effects at that point [15].

The ultimate tensile strength of the welded joint increased with an increase of the heat input, while, too high a heat input resulted in a decrease of the ultimate tensile strength of the welded joint. In addition, the average micro hardness of the heat-affected zone and fusion zone decreased sharply with an increase of the heat input and then decreased slowly at a relatively high heat input. An increase of heat input resulted in an increase of the width of HAZ and the grain coarsening of grain in both the HAZ and FZ. In general, the UTS of welded joints increased with an increase of the heat input because too low a heat input led to the presence of partial penetration and pores. However, too high a heat input decreased the UTS of welded joints slightly due to the evaporation of the zinc from the aluminium alloy. The tensile fracture of the welded joints usually occurred in the HAZ and the fracture surfaces of the welded joints were characterized by brittle and ductile components. The micro hardness of the HAZ was lower than that of the BM and FZ due to the grain coarsening in the HAZ. With an increase of heat input, the micro hardness of both the HAZ and FZ decreased sharply at first and then decreased slightly due to the formation of the granular phase when a relatively high heat input was used [16].

As the heat input source increases deeper weld penetration, higher welding speeds, and better weld quality with less damage to the workpiece, the weld strength of aluminum alloys, increases as the heat input per unit length of the weld per unit thickness of the workpiece decreases [17].

1.3.9 Joint Design and Preparation.

Problems with weld quality or performance can often be attributed to the wrong design of edge preparation. Joint design is determined by the strength requirements, the alloy, and the thickness of the material, the type and location of the joint, the access for welding and the welding process to be used. There are three fundamental forms of weld, the butt, the fillet and the edge weld. The static tensile strength of these weld types is determined by the throat thickness (Fig.3 (a)). The size of a fully penetrated butt weld is determined by the thickness of weld metal deposited within the plane of the plate or pipe, t_1 in Fig.3. (a). No credit is taken in calculating permissible static design stress of either a butt or fillet weld for the excess weld metal, i.e. that above the surface of the parent metal for a butt or out tside the isosceles triangle of a fillet weld as given by $(t_2 - t_1)$ [3] .

The butt weld, typical forms of which are illustrated in Fig.3.(a), is a simple and easily designed joint which uses the minimum amount of material. Fig.3 (b) also includes definitions of some of the features of a weld preparation such as ‘root face’, ‘angle of bevel’ and ‘included angle’. Butt welds with the conventional fusion welding processes of TIG and MIG penetration of weld metal into the surface of a flat plate from a bead-on-plate run is typically 3mm and 6mm respectively. To achieve a full penetration butt weld at thicknesses over these it is necessary for the two close square butted edges to be bevelled, although leaving a small gap between the edges will increase penetration. Typical weld preparations for the various processes will be found in the relevant process chapter. Butt joints may be single or double sided – if double sided it is often necessary to back-gouge or back-grind the first side to be welded to achieve a joint that is free of any lack of penetration [3].

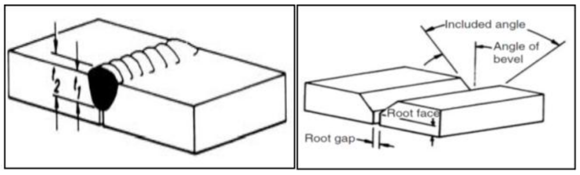

Fig .3. (a) **Fig.3. (b)**

Fig. 3.(a) Throat thickness in a butt weld
Fig.3. (b) Features of a weld preparation.

The effective size of a full penetration butt weld equals the design throat thickness, essentially the plate/pipe thickness of the thinner component. Usually no credit is taken for the weld metal cap height or root penetration bead. Although not often used in aluminium fabrications because of the need to match joint strength and base metal strength, in lightly loaded joints a partial penetration joint, may be acceptable. Partial penetration can be achieved by the use of a close square butt joint or a thick root face. There is cost benefits associated with the partial penetration joint as little or no edge preparation is required, it is economical on filler metal and it is easy to assemble since the root gap does not need to be controlled. The limitations are that radiographic interpretation is difficult due to the lack of penetration, the fatigue life is compromised and static mechanical strength is reduced. The effective size in the case of the partial penetration weld is the throat of the weld minus the cap height [3].

The strength of a sound, defect-free butt weld generally matches that of the filler metal or the annealed strength of the parent metal. The butt joint is the best in a dynamic loading environment, particularly if the excess weld metal is dressed flush. To achieve the best properties the two component parts require accurate alignment, which implies adequate tacking, jigging and fixturing [3].Although it is possible to deposit a sealing run on the reverse side of a butt weld without a back-gouge, this cannot be relied upon to give a sound, defect-free weld. The purpose of the backing bar or strip is to support the root pass where conditions make the control of the bead difficult. Conventionally, a backing bar is temporary and can be lifted away as soon as the weld has been completed. Backing bar material can be inexpensive mild steel but a longer life can be obtained from the bar with less risk of contamination if stainless steel is used. Typical designs of backing bars and strips are given in Fig.4

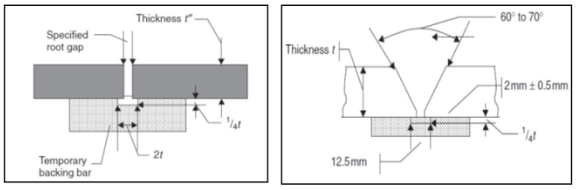

Fig.4. Typical designs of backing bars and strips

Aluminum alloys are very popular in the industrial world as structural materials, mainly due to their high strength to weight ratio. The automobile and aircraft industries are two examples where aluminum alloys are definitely the materials of choice. Especially in the aircraft industry, it is very important to reduce the weight of airplanes as much as possible [1]. High strength aluminium alloy AA7075T6 alloy has gathered wide acceptance in the fabrication of light weight structures requiring high strength-to-weight ratio, such as transportable bridge girders, military vehicles, road tankers and railway transport systems. The preferred welding processes of high strength aluminium alloy are frequently gas tungsten arc welding (GTAW) process and gas metal arc welding (GMAW) process due to their comparatively easier applicability and better economy [9].

2. **Problems in fusion welding of high strength aluminium alloy.**

Pure aluminium has very low strength, yet many of its alloys are stronger than ordinary structural steels. Some aluminium alloys especially those in the 5XXX and 7XXX series e.g., 5083, 7020, and 7039 are so strong that they could be used in armour structures. The 7XXX series alloys are heat-treatable Al-Zn-Mg or Al-Zn-Mg-Cu alloys. They develop their strength by solution heat treatment followed by ageing. In contrast to the 5XXX series alloys, the 7XXX series alloys do not respond favourably to cold work, because they are strengthened almost exclusively by GP zone formation and precipitates which nucleate from the GP zones. Introducing many new dislocations by cold work after solution treatment and quenching does not greatly accelerate formation of precipitates [19]. Aluminium alloys can be joined by most fusion and solid-state welding processes as well as by brazing and soldering, but here concerned with inert gas tungsten arc welding (GTAW or TIG) only, because this is the most commonly used welding processes for joining AA7075T6 alloy. The following are the main three problems associated with welding of high strength aluminium alloys AA7075 T6 are discussed:

Porosity;
Oxide film removal during welding;
Hot cracking;
Stress corrosion cracking (SCC);
Strength loss due to welding;

Porosity is a common problem in welding of all types of aluminium alloys. Hot cracking and SCC may appear in welded joints of 7XXX series alloys but usually do not occur in 5XXX series alloys. With above mentioned problems there is Loss of strength in the weld metal and heat affected zone is mainly due to the dissolution of strengthening precipitates during melting and high cooling rates involved in welding. And the loss of strength also due to the melting and quick resolidification, which renders all the strengthening precipitates to dissolve and the material is just as good as solution treated [19].

2.1 Porosity

Porosity is a problem confined to the weld metal. It arises from gas dissolved in the molten weld metal becoming trapped as it solidifies, thus forming bubbles in the solidified weld as shown in Fig.5 [3].

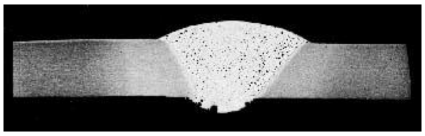

Fig.5. Forming bubbles in the solidified weld.

Porosity can range from being extremely fine micro-porosity, to coarse pores 3 or 4 mm in diameter. The culprit in the case of aluminium is hydrogen, which has high solubility in molten aluminium but very low solubility in the solid, as illustrated in Fig.6. This shows a decrease of solubility to the order of 20 times as solidification takes place, a drop in solubility so pronounced that it is extremely difficult to produce a porosity-free weld in aluminium [3].

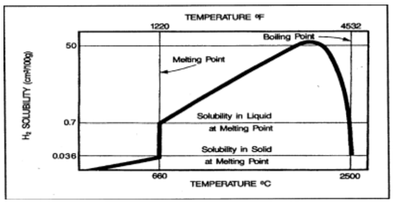

Fig.6. Solubility of hydrogen in aluminium.

Although porosity is almost unavoidable in gas-shielded welding processes; it usually does not pose any serious problem in welding of steels. However, porosity is the major cause for rejection of aluminium welds by various non-destructive testing codes. This highlights the need to understand mechanisms of porosity formation in aluminium welds and methods of reducing the porosity level. The main source of porosity is hydrogen contamination. Solubility of hydrogen in superheated liquid aluminium is very high but is drastically reduced in solidified aluminium. Therefore, when solidification takes place in the welding pool, the excessive hydrogen will form “bubbles” gradually, and the “bubbles” will be trapped in the weld to become porosity if they cannot escape to air before the solidification is complete. In steel welds, porosity is less a problem for two reasons: First, when steel solidifies, hydrogen solubility also reduces a lot, but the reduction is not so drastic as in process of aluminium solidification; Second, the solidification temperature range of steel is roughly two times greater than aluminium, and the thermal conductivity of steel is only about one-quarter that of aluminium, so solidification takes place much more slowly in steel than in aluminium, making it considerably easier for the “bubbles” in the welding pool of steel to escape. Hydrogen can enter the arc column of welds deposited by TIG and MIG from a variety of sources such as [19]:

(1) Hydrogen within the filler metal and parent metal;
(2) Hydrogen-containing contamination (*e.g.*, oil, greases and solvents) or hydrated oxide films on the surfaces of the filler wire and parent metal;
(3) Moisture in the shielding gas.

The greatest single source of porosity is the surface contamination of the filler wire, and the resulting porosity is greater in MIG than in TIG due to the high ratio of surface area to volume of the filler metal required for MIG[19].

One of the most effective methods to reduce porosity is to control the weld bead shape. Narrow and deep welds tend to trap porosity since individual pores must raise a long distance to escape to the surface. Compared with downhill welding, uphill welding provides a shorter vertical path for hydrogen bubbles to escape before weld solidification is complete and thus produces fewer surface and internal pores [19].

Turbulent convective fluid flow by electromagnetic stirring during solidification has been shown to produce a substantial reduction in porosity and grain size in aluminium alloys deposited by the TIG process [19].

Radiography indicates only the macro-porosity as discrete pores. In general, there is 5 to 10 times more micro-porosity than macro-porosity, and both the macro- and micro-porosity affect the mechanical properties of the weld metal. The micro-porosity as well as the macro porosity can be revealed clearly under the optical microscope by metallographic examination and measured quantitatively using an image analyser connected to the microscope [19].

2.2. Oxide film removal during welding.

There is a presence of a tenacious oxide layer over every aluminum alloy Fig.7.it having the following properties [20].

- Melting point more than 2000°C.
- Weather and corrosion resistance in oxidative circumstances.
- Good wear hardness.
    - strongest material after diamond
- Transparent material.
- Thickness of oxide grows hastily until 10 nm (0,000010 mm).
- It can grow electrolytic and chemically until 0,05 - 0,1 mm.
    - anodic oxidization.
    - Coloring.
- When oxide grows thick, it comes more porosity.
- Aluminium base material produced oxide layer when it reacts with oxygen.
- It has power of regeneration
    – When oxide layer is damaged, it grows up itself again.

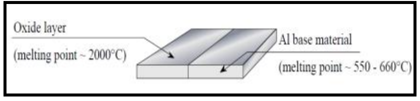

Fig.7. Presence of oxide layer over aluminum alloy.

All aluminium alloys have a thin oxide films on aluminium alloys thicken with time, so prolonged storage after cleaning and before welding increases the porosity level and should be avoided. Welding using small current and short arc length helps to reduce porosity level [19].

The need to remove the oxide film prior to welding is necessary to reduce the risk of porosity. It is also necessary to disperse this film during welding if defects such as lack of fusion and oxide film entrapment are to be avoided. In welding of aluminium alloys oxide film removed by using AC where oxide film removal takes place on the positive half cycle and electrode cooling on the negative half cycle as illustrated in Fig.8.TIG welding of aluminium is therefore normally carried out with AC [3].

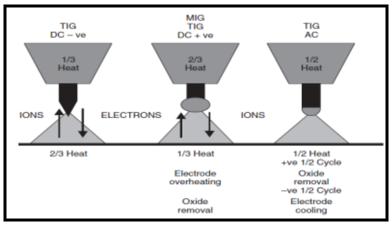

Fig.8.Effect of polarity on cathodic cleaning and heat balance.

The surface of aluminium oxide is quite porous, and it can retain moisture or contaminants that may result in weld porosity. This is especially true of alloys containing magnesium oxide or magnesium aluminium oxide readily hydrates. Thus it is good practice to keep aluminium clean and dry and to avoid temperature fluctuation that lead to condensation. Thick oxide layer should be removed prior to welding since it can introduce hydrogen and other contaminants in to the weld pool [3].

2.3 Hot cracking

Hot cracking is a potential problem in TIG or MIG welding of some 7XXX series aluminium alloys. As the name indicates, this kind of cracking occurs while the metal is still hot. It usually occurs in the fusion zone during solidification, so it is also called solidification cracking. Hot cracking may also occur in HAZs if some grains there are partially melted during welding. The partial melting may take place at grain boundaries which have low melting points due to chemical segregation. Hot cracking in HAZs is often referred to as liquation cracking, since it occurs at liquated grain boundaries only. It is generally accepted that hot cracking occurs during the final stage of solidification and is associated with the existence of small amounts of segregate-rich low melting point liquid separating solid grains. Cracking occurs when the stresses developed across the adjacent grains exceed the strength of the almost solidified weld metal. Such stresses can be induced by solidification shrinkage of the weld metal and thermal contraction of the workplace, which are both significant with aluminium alloys. When hot cracks occur at the early stage of solidification, they may be easily refilled by the remaining low melting point liquid. However, this “healing” process becomes more and more difficult as the remaining volume of liquid decreases and the paths between grains become more restricted [19].The aluminium alloys all exhibit a peak in sensitivity with a high resistance to hot cracking at both low and high alloy content, as shown in Fig 8.

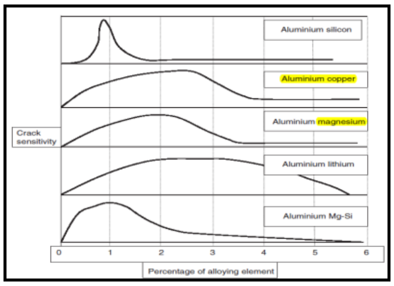

Fig.8.Effect of solute concentration on crack sensitivity.

At low levels of alloy content there is only a small amount of eutectic present. This results in the liquid film on the grain boundaries being either discontinuous or very thin. In summary, if hot cracking is encountered it may be eliminated by one or more of the following [3]:

- A small grain size. It has been found that small additions of elements such as titanium, zirconium or scandium will act as nuclei for the formation of a very fine grain during solidification. Filler metals can be purchased that are alloyed with titanium and/or zirconium or scandium.
- Control the composition of the weld pool by adding filler metal to produce an alloy that is not in the hot short range.
- Use an edge preparation and joint spacing to permit sufficient filler metal to be added to achieve a weld metal composition outside the hot short range.
- Use the highest welding speed. High speeds reduce the length of time the weld is within the hot short temperature range. High welding speeds also reduce the size of the HAZ and consequently the shrinkage stresses across the joint.
- Use high-speed, small-volume multi-run procedures instead of large volume, single run deposits.
- Select welding and assembly sequences that minimise restraint and residual stresses.
- Apply an external force to maintain the weld in compression while it is in the hot short range.
- Select a filler metal with a melting point close to that of the parent metal.

The hot cracking susceptibility of high strength 7XXX series aluminium alloys, as in other alloys, is strongly affected by the chemical composition of the weld metal. For example, crack susceptibility increases with increasing Cu content when Cu content is below 3% and reduces with increasing Cu content when Cu content is above 3%. The resistance to cracking is enhanced by the addition of grain refining agents such as Zr in the alloy. Hot cracking can be avoided by using proper filler wires and dilution ratios to control the weld metal composition [19].

2.4 Stress corrosion cracking.

It was reported in The Straits Times of 22 Feb. 1993 that almost half of Thailand’s Stingray battle tank developed faults or cracks after a few years’ service. The armour of the battle tank is made of a high strength aluminium alloy. The likely cause for the structural defects is Stress Corrosion Cracking (SCC) [19].

For SCC to occur, three conditions must be met:

- Susceptible microstructures;
- Corrosive environments (which do not necessarily cause general chemical corrosion);
- Tensile stresses.

The 7XXX series aluminium alloys are more susceptible to SCC than the 5XXX series aluminium alloys. Medium-strength, low copper, and copper free 7XXX alloys have been developed for a variety of engineering properties. Most 7XXX series aluminium alloys have excellent SCC resistance in the longitudinal direction and good SCC resistance in the transverse direction but relatively poor resistance in the short-transverse direction (*i.e.*, thickness direction) [19].

Because of the orientation dependence of SCC in aluminium alloys, stresses in the most susceptible direction usually, the short-transverse direction must be avoided or minimised. In addition to operating stresses, SCC can result from residual forming or welding stresses, stresses introduced by machining operations, and stresses from misfit of parts being assembled. It is these residual stresses, rather than operating stresses, that are most often responsible for SCC failure, because they may be overlooked during the design process [19].

The welding residual stresses in the short-transverse direction may be very high for T welded joints or corner joints, but it is possible to limit the stresses to low levels through the use of soft weld overlays or by proper welded-joint design or choice of welding parameters. Reducing stresses in the short-transverse direction to a minimum greatly reduces the likelihood of SCC failure in susceptible alloys [19].

Heat treatment or tempering affects corrosion resistance and mechanical strength by controlling the distribution of alloying elements between solid solution and insoluble precipitates. To minimise SCC susceptibility, over-ageing treatments (T7) may be utilized at some sacrifice of tensile strength. However, tempering or heating during welding may be undesirable and reduce SCC resistance of the welded joints. For example, in alloy AA 7017 white zones due to MIG welding were found to be more susceptible to SCC than the parent material in T651 temper. For heat treatable 7XXX series, thermal treatment after welding is sometimes used to obtain maximum corrosion resistance [19].

2.5 Strength loss due to welding.

In order to effect a weld the components to be joined are heated to a high temperature, in the case of fusion welding above the melting point of the parent metals, and brought together to enable the components to coalesce. The heat of the welding operation is conducted into the parent metal such that in any welded joint there are three distinct areas – the weld metal in a fusion welded joint, the HAZ in the parent material and the unaffected parent metal. The HAZ may be further subdivided into areas with particular properties depending upon the alloy system involved. Since the HAZ will have experienced one or more cycles of heating and cooling the properties may be radically different from those of the unaffected parent metal. This is particularly the case with those aluminium alloys that have been strengthened by either cold working or precipitation hardening. One aspect of this is the width of the HAZ, a function of the high thermal conductivity of aluminium and the consequent size of the area where there has been a substantial loss of strength. Only when the alloy is in the as-cast or annealed condition will the properties of the HAZ match those of the parent metal [3].

2.5.1 Weld metal.

In a fusion weld the weld metal is an as-cast structure consisting of a mixture of the filler metal, if added, and the parent metal. The properties of this weld depend upon the composition, the quality and the grain size of the deposit. These in their turn depend on the parent and filler metal compositions, the amount of dilution, the quality of the welding process and the welder and, lastly, the rate of solidification. With the exception of a couple of 2XXX filler wires most filler metals available are not capable of being age hardened, although dilution with parent metal may enable some age hardening to take place. Fast solidification rates will give a finer grain size and hence better mechanical properties than slow solidification rates. Small weld beads therefore generally have better properties than large weld beads and a higher resistance to hot cracking. In the root pass, however, a small cross-section weld bead may increase the risk as it will be required to carry the contractional stresses and restraint [3].

There is very little that can be done to improve the properties of the weld metal. Solid solution strengthening can be useful and the selection of the appropriate filler metal can significantly contribute to a high weld metal strength. As a general rule the weld metal will match the parent metal properties only when the parent metal itself is in either the as-cast or annealed condition. Where cold work has been used to increase the strength of the parent metal it is not practicable to match these by cold working the weld. The lower strength in the weld metal must therefore be accepted and compensated for in the design. With some of the precipitation-hardening alloys a post-weld ageing treatment can be carried out to increase the strength of the weld metal, provided that the weld metal contains those alloying elements which will give precipitation hardening as mentioned above. The effectiveness of this heat treatment will depend upon the filler metal composition and dilution [3].

2.5.2 Heat affected zone.

If aluminium alloys are in as-cast or annealed condition may be welded without any significant loss of strength in the HAZ, the strength of the weldment matching that of the parent metal. Where the alloy has had its strength enhanced by cold work or precipitation hardening then there may be a substantial loss of strength in the HAZ [3].

The cold worked alloys will experience a loss of strength due to recrystallisation in the HAZ. Recrystallisation begins to take place when the temperature in the HAZ exceeds 200 °C and progressively increases with full annealing taking place over 300 °C.

A similar picture can be seen in the heat-treatable alloys. The situation here is somewhat more complex than with the work-hardened alloys but similar losses in tensile strength can be found. The loss is caused by dissolution of the precipitates in the 2XXX series alloys and a coarsening or over ageing of the precipitates in the 6XXX and 7XXX alloys. The loss of alloying elements from the weld pool may result in a reduction in strength. It is true that some elements, mainly magnesium with its low boiling point and lithium which is highly reactive with oxygen, may be lost or oxidized during welding. There is, however, a dearth of information quantifying any effects, which suggests that it is not perceived as being a problem. Loss of magnesium is worst when MIG welding, resulting in the sooty deposit occasionally seen along the weld toes but in this case, and in the case of lithium, careful attention to gas shielding will minimize any problem [3].

3. Effect on mechanical properties of fusion welded joints of aluminium alloy.

In any welding process, the input parameters have influence on mechanical properties of the joint. By varying the input process parameters combination, the output would be different welded joints with significant variation in their mechanical properties. Accordingly, welding is usually done with the aim of getting a welded joint with excellent mechanical properties. To determine these welding combinations that would lead to excellent mechanical properties, different methods and approaches have been used to achieve this aim. The following is a review of some articles that utilized these techniques for the purpose of optimizing the welding process parameters in order to achieve the desired mechanical properties of the welded joint [20].

The mechanical properties of weld joints are mainly controlled by welding defects, composition, microstructure and metallurgical states of weld metal and neighboring base metal. The presence of defects will reduce the mechanical properties of the joints. Alloy composition dominates solid solution and precipitation strengthening. Selective vaporization of volatile constituents from the fusion welded FZ degrades the mechanical properties of the weld metal. The loss of tensile strength for the precipitation-hardened alloys is caused by dissolution of the precipitate phases and the presence of weld defects such as porosity and hot cracking [1].

In contrast to steel generally showing an increased hardness in the weld zone due to martensitic hardening, in the case of aluminum alloys the effect of precipitation or work hardening is destroyed partially or totally by the heat load of the laser welding process. The amount of thermal damage is considerably lower than with arc welding, however, and decreases with increasing heat quantity, allowing higher welding speed. In the case of heat-treatable alloys, the loss of precipitates in the welds and over aging in the HAZ has been identified as the main cause of hardness reduction. Solution and aging heat treatments after welding can be used to recover the hardness to the level of the base metal. However, it is undesirable to perform solution treatment at high temperatures after welding. Natural aging usually cannot achieve recovery of a hardness level within the FZ and the HAZ comparable to that of the base metal [1].

Welded joints fabricated by GMAW process have lower strength, compared with GTAW values and the enhancement in strength value is approximately 28%. Hardness is lower in the weld metal (WM) region compared to the HAZ and BM regions. Higher hardness is recorded in the GTAW (HAZ) and the maximum Hardness of 157 VHN was observed in the HAZ. In the parent metal 153VHN is recorded. In GMAW (HAZ) also high Hardness of 133 VHN was observed. In the parent metal 100.5VHN is recorded. In GTAW 6J and GMAW 4J value was observed. Fine, equiaxed grains were formed in the welding zone and they were uniformly distributed in the microstructure. The SEM image shows that the fracture is brittle in nature [21].

The influence of pulsed welding parameters such as peak current, base current, welding speed, and frequency on mechanical properties such as ultimate tensile strength (UTS), yield strength, percent elongation and hardness of AA 7017 aluminum alloy weldments have been studied. And it was found that optimum combination is observed in all the mechanical properties of welds. The behavior of the welded joints at the optimum condition of process parameters is attributed to increase an amount of Mg_2Al_3 precipitates that are formed in the aluminum matrix. In addition, the metallographic analysis reveals a fine grain structure at the weld centre, which results in higher mechanical properties. It is observed that, there is 10–15% improvement in mechanical properties after planishing. This is due to fact that, internal stresses are relieved or redistributed in the weld [22].

An empirical relationship was developed to predict tensile strength of pulsed current gas tungsten arc welded AZ31B magnesium alloy using response surface methodology. The developed relationship can be effectively used to predict the tensile strength of pulsed current gas tungsten arc welded joints at 95% confidence level. A maximum tensile strength of 188 MPa was obtained under the welding condition of peak current of 210 A, base current of 80 A, pulse frequency of 6 Hz and pulse on time of 50%, which is the optimum PCGTA welding condition for AZ31B magnesium alloy and confirmed by RSM. Pulse frequency has the greatest influence on tensile strength, followed by peak current, pulse on time and base current [23].

4. Outlook

To weld high strength aluminium AA 7xxx series alloy with high productivity, high quality and low cost, a predictable, repeatable, consistent and reliability, the welding process need to be developed. Wider welding operating windows are also welcome for industrial applications. Thus, further efforts should concentrate on optimizing, controlling, regulating and defining GTAW welding parameter-operating windows for different high strength aluminium AA7xxx series alloys. Process specifications for GTAW should be developed to avoid the occurrence of welding defects for the reliable production of high strength Aluminium AA 7xxx series alloy joints. Research work on modeling and simulation will aid in the understanding of the welding processes involved [24]. Little work in this aspect, however, has been conducted to date. No quality standards for GTAW welded high strength aluminium alloy AA 7xxx series alloy are available at the moment. Defect assessment procedures specific to the GTAW welded joints are also needed. There is also a requirement to establish the comprehensive relationships of material, welding processes and defects with mechanical properties of GTAW welded joints including tensile, fatigue, fracture, formability and other static and dynamic properties, as well as corrosion properties. Limited work has ever been reported on the control of tensile, hardness, residual stress and distortion in GTAW welded high strength aluminium AA 7xxx series alloy. Dissimilar joints between different high strength aluminium AA 7xxx series alloys, dissimilar metals and composites, with different geometries, will probably be GTAW welded in the future.

5. Summary.

GTAW welding will probably become an important joining technique for high strength aluminium alloy AA 7xxx series alloy and can promote their wider uses in aerospace, aircraft, automotive, electronics and other industries. To date, GTAW have been used to investigate the weldability of high strength aluminium AA 7xxx series alloy. Crack-free welded joints with low porosity and good surface quality. Due to their inherent properties, high strength aluminium AA 7xxx series alloy may exhibit some processing problems and weld defects such as porosity, unstable weld pool, undercut, liquation and solidification cracking, oxide inclusions and loss of alloying elements. In future scientific investigation is still needed to understand and overcome these basic weldability problems of high strength Aluminium AA 7xxx series alloy.

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