EFFECT OF WELD PARAMETERS ON THE PROPERTIES OF ALUMINIUM WELDMENT

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering (MME) at Bangladesh University of Engineering and Technology, Dhaka.
DECLARATION

This is to certify that this work has been carried out by the author under the supervision of Dr. Quamrul Ahsan, Department of Materials and Metallurgical Engineering, BUET, Dhaka and it has not been submitted elsewhere for the award of any degree or diploma.

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ABSTRACT

Two different grades of aluminium plates (1xxx and 5xxx series) were welded with two different filler metals (4043 and 5356) and with different current settings of 145A, 175A and 195A. Tungsten Inert Gas (TIG) welding process was used for welding. During welding at different conditions various eutectics, intermetallic compounds and phases formed at different temperatures and at different compositions. All of these phases contributed to a change in mechanical properties. In the present research, a systematic investigation was made on TIG welding of aluminium alloy to determine the probable reasons for evolution of solidification cracking of aluminium weld and to improve the structure-property relationship of weldment by controlling heat input. It was expected that the research work will optimize the process parameter to find out an optimum condition for welding.

When 4043 filler metal (Al-5% Si) was used for welding pure aluminium plates (1xxx series) a secondary phase formed during welding. It was identified as Al-Si eutectic mixture and was different in size, shape and orientation not only at different current setting but also at different location of the welded samples. It was observed that at the highest current setting that is at the highest heat input the eutectic mixture was coarsest and largest in size and tends to form a continuous network. On the other hand at low heat inputs the eutectic mixture did not get sufficient time to grow or to form any continuous network. The change in microstructure with heat input is also supported by the micro and macro hardness values of these plates. As a result the hardness value was the highest at the coarsest and largest eutectic mixtures. In each current setting there was dilution of the eutectic mixture in the heat affected zone. It was also observed that difference in hardness values between different portions of the weld decreases as the welding current increases because high heat input created more dilution in the weld structure.

Again when 5356 filler metal (Al-5%Mg) was used for welding pure aluminium plates, another type of secondary phase was found during welding and it was identified as globules of MgAl2 precipitates. Here also the precipitates were different in size, shape and orientation at different current settings and at different locations of the welded samples. In this case solidification
cracking appeared in the heat affected zone and in the weld portion. Here the tendency for this defect decreased in the case when there was sufficient time for solidification after welding and when the temperature difference between the precipitates and the bulk material decreased. As a result when welding conducted at the highest current setting the tendency for solidification cracking decreased.

Another set of welding was performed using a base plate of 5xxx series (Al-Mg alloy). Here two different current setting of 145A and 175 A were used. In this case when 4043 filler metal was used for welding again Al-Si eutectic mixture formed but another phase of Mg2Si also formed during welding. The characteristics of the eutectic mixture was the same as the previous welding that is at the highest current setting the eutectic mixture was the largest, coarsest and continuous in nature. However another phase of Mg2Si was also found and suspected to be responsible for deteriorating the impact energy. In this case the microhardness profiles exhibit that increase in current content results in structural homogeneity. Finally another base plate of 5xxx series was welded at a current setting of 175 A with 5356 (Al-Mg) filler metal and it needs further studies to explain the characteristics of this welded samples.
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INTRODUCTION

Aluminium and its alloys are widely used in fabrications because of their light weight, good corrosion resistance and weldability. The unique combination of light weight and relatively high strength makes aluminium the second most popular metal that is welded. Aluminium/Aluminium alloy possesses a number of properties such as oxidation, solubility of gas and change in strength that make its welding different from the welding of steels. Aluminium or aluminium alloys are usually fusion welded with widely used tungsten inert gas welding (TIG) process in which inert gas (Ar, He) is supplied to reduce the oxidation of weld metal.

An increased use of aluminium in the automotive and ship building industry in Bangladesh has resulted in renewed interest in the weldability of aluminium alloys. A large number of weldable parts in different industries often cause premature failure due to lack of proper knowledge on weldability of aluminium alloys. Even small cast parts are discarded when they encountered casting and machining defects. With improved weld deposition process most of these products may be repaired and put into the service. In addition, large and complex shape components can be manufactured by assembling small sized objects with proper joining methods. These processes may save in recast or fabricating cost.

Some of the most common problems encountered in any aluminium welds and need control are porosity, cracking and filler alloy selection. Ductility, fatigue strength and tensile strength of welded joints are adversely affected by the inclusion of porosity. Porosity in aluminium weld originates from entrapped gases within the weld puddle. Contaminants in the shielding gas, air, and water as well as contaminants in the base or filler metals can be the origin of these gases. During welding, partially melted
zone is formed immediately outside the weld, where liquation can occur and lead to hot cracking.

When welding steel, the selection of a filler alloy is often based on the tensile strength of the base alloy alone. The selection of filler alloy for aluminium is typically not that simple and is usually not based solely on the tensile strength of the completed weld. The variables which need to be considered during filler alloy selection are: case of welding, strength of the weld, weld ductility, service temperature, corrosion resistance and post weld heat treatment.

In the present research, a systematic investigation was made on TIG welding of aluminium alloy:

I. To determine the probable reasons for evolution of weld porosity and the solidification cracking of aluminium weld.
II. To improve the structure - property relationship of weldment by controlling heat input.

It was expected that the research work will optimize the process parameter and will lead to a cost-effective joining method that will be adopted by the fabricator. This will somewhat reduce the material loss and fabrication cost.
2.1. CHARACTERISTICS OF ALUMINIUM

The main physical and chemical characteristics of aluminium which should be considered during welding are listed below. (King, F. 1987)

- Aluminium oxide melts at 2060°C, some 1400°C above the melting point of aluminium. This has important implications for the welding process, since it is essential to remove and disperse this oxide film before and during welding in order to achieve the required weld quality.

- The oxide film on aluminium is durable, highly tenacious and self-healing. This gives the aluminium alloys excellent corrosion resistance, enabling them to be used in exposed applications without additional protection. This corrosion resistance can be improved further by anodising - the formation of an oxide film of a controlled thickness.

- The coefficient of thermal expansion of aluminium is $31.1 \times 10^{-6}$ /°C (at 500°C) which cause unacceptable buckling and distortion during welding.

- The coefficient of thermal conductivity of aluminium is also very high, thus the heat source for welding aluminium needs to be high and concentrated. This is particularly
so for thick sections, where the fusion welding processes can produce lack of fusion defects if heat loss is too rapid.

- Aluminium has high electrical conductivity, only three-quarters that of copper but six times that of steel. This is a disadvantage in case of resistance spot welding where the heat for welding must be produced by electrical resistance.

- Aluminium does not change colour as its temperature rises. This can make it difficult for the welder to judge when melting is about to occur, making it imperative that adequate retraining of the welder takes place during aluminium welding.

- Aluminium is non-magnetic which means that arc blow is eliminated as a welding problem.

- Aluminium has a modulus of elasticity three times that of steel which means that it deflects three times as much as steel under load but can absorb more energy on impact loading.

- The fact that aluminium has a face-centred cubic crystal structure means that it does not suffer from a loss of notch toughness as the temperature is reduced. In fact, some of the alloys show an improvement in tensile strength and ductility as the temperature falls. This crystal structure also means that formability is very good, enabling products to be produced by such means as extrusion, deep drawing and high energy rate forming.

- Aluminium does not change its crystal structure on heating and cooling. As a result changes in the cooling rate have little or no effect on the aluminium alloys.
2.2 ALLOYING ELEMENTS

Aluminium of the purity obtained from the electrolytic reduction of alumina is a relatively weak material. For applications requiring greater mechanical strength it is alloyed with other elements. The principal alloying elements are copper, silicon, manganese, magnesium, lithium and zinc. Elements such as nickel, chromium, titanium, zirconium and scandium may be added in small amounts to achieve specific properties. Other elements may also be present in small amounts as unwanted impurities. These elements, known as tramp or residual elements, have no beneficial effects on mechanical properties. The main effects of the alloying elements are as follows: (Mathieson G,

- Magnesium (Mg) increases strength through solid solution strengthening and improves work hardening ability.
- Manganese (Mn) increases strength through solid solution strengthening and improves work hardening ability.
- Copper (Cu) gives substantial increases in strength, permits precipitation hardening, reduces corrosion resistance, ductility and weld ability.
- Silicon (Si) increases strength and ductility, in combination with magnesium produces precipitation hardening.
- Zinc (Zn) substantially increases strength, permits precipitation hardening, can cause stress corrosion.
- Iron (Fe) increases strength of pure aluminium, generally residual element.
- Chromium (Cr) increases stress corrosion resistance.
- Nickel (Ni) improves elevated temperature strength.
- Titanium (Ti) used as a grain-refining element, particularly in filler metals.
- Zirconium (Zr) used as a grain-refining element, particularly in filler metals.
- Lithium (Li) substantially increases strength and Young's modulus, provides precipitation hardening, decreases density.
- Scandium (Sc) substantially increases strength by age hardening, grain-refining element particularly in weld metal.
- Lead (Pb) and bismuth (Bi) assist chip formation in free machining alloys.
2.3 MATERIAL TYPES

The alloys covered by standards can be divided and considered in two main groups, namely those used for castings and those to be fabricated into wrought forms. For ease of reference these will be referred to by the BS 1490 LM designations for alloys for castings and for wrought alloys by the internationally agreed four digit system in which the first of the four digits in the designation indicates the major alloying element of alloys within the group as follows: (Mathers C,

\[ \begin{align*}
1xxx & \quad \text{Aluminium of 99 percent minimum purity} \\
2xxx & \quad \text{Copper} \\
3xxx & \quad \text{Manganese} \\
4xxx & \quad \text{Silicon} \\
5xxx & \quad \text{Magnesium} \\
6xxx & \quad \text{Magnesium plus silicon} \\
7xxx & \quad \text{Zinc} \\
8xxx & \quad \text{Other elements} \\
9xxx & \quad \text{Unused series}
\end{align*} \]
The alloys can be further classified according to the means by which the alloying elements develop mechanical properties, non-heat-treatable or heat-treatable alloys. (Figure 2.1)

Figure 2.1. Classification of aluminium alloys

In the present research work two different grades (1xxx and 5xxx) of aluminium alloys were used as base metal and two different filler metals (4xxx and 5xxx) were used for welding. Discussion will be made on these alloys only.
2.4 EQUILIBRIUM DIAGRAMS OF ALUMINIUM ALLOYS SYSTEMS

The properties of an alloy are determined by its crystal structure which may include a number of phases differing in composition and depending on temperature. Equilibrium diagrams represent the relationships between temperature and composition of the phases in an alloy system in equilibrium. But most metallic materials in industry are not in equilibrium. Nevertheless equilibrium diagrams provide guidance and a source of understanding of the reactions which take place in commercial alloys which, in addition to the main alloying elements, normally contain impurities in quantities which can have important effects on the constitution, such as introducing new phases and other modifications in the structure. Commercial alloys are seldom cast and processed under conditions which are conducive to the establishment of equilibrium, but nevertheless the diagrams provide valuable guidance to the behaviour of the alloys in practice.

2.4.1 1XXX GROUP (PURE ALUMINIUM)

The main impurities in pure aluminium will normally be iron and silicon, with the possible presence of copper or zinc in quantities of less than 0.1 wt% and other elements in quantities of less than 0.5% each, totalling less than 0.15%. The diagram of the binary aluminium-iron system is shown in figure 2.2. The aluminium-silicon binary alloys are dealt with in the section on 4xxx alloys.

The aluminium-iron alloys form a eutectic series with very small solid solubility, the eutectic between the constituent designated FeAl, and aluminium lying at 1.7% iron and 655°C at which temperature the aluminium-rich solid solution contains 0.052% iron. The solid solubility decreases with the temperature, being 0.25% at 600°C and 0.006% at 500°C. However these values can be achieved only by prolonged annealing followed by quenching, so that aluminium, even super purity metal, will normally contain particles of iron-bearing constituents. (King, P. 1987)
Figure 2.2. Binary diagram of aluminium-iron system.

Silicon is also a normal impurity in aluminium, so it is necessary to study the aluminium-rich corner of the aluminium-iron-silicon ternary diagrams. (Figure 2.3 and figure 2.4)

Figure 2.3. Equilibrium diagram: Aluminium-iron-silicon solidus surface
Isothermal sections for temperatures below the solidus are all replicas of the phase boundaries of the solidus surface. With falling temperature the apices of the three phase triangles move towards the aluminium corner of the model.

A ternary alloy of aluminium may contain three and possibly more constituents in addition to the aluminium rich solid solution and the phases, FeAl₃ and silicon of the binary systems. Two of the ternary phases have fairly wide homogeneity ranges: α (FeSi) extends from 8 to 10 percent silicon at 33 percent iron and β (FeSi) from 13.5 to 15.5 percent silicon at 27 percent iron; δ (FeSi) has a small homogeneity range round the composition 25 percent silicon – 25.5 percent iron.

Undercooling can result in a shift of the primary field boundaries. Rapid solidification prevents the aluminium phase from taking up iron or silicon to the saturation point, with the result that the liquid phase becomes enriched in these elements and deposits them in the form of eutectics. Silicon therefore appears in the microsections if the amount present exceeds about 0.25%, and FeAl₃ appears at about 0.02 percent iron (Figure 2.4). In commercially pure aluminium, where silicon is invariably present, one or both of the ternary compounds α (FeSi) and β (FeSi) may occur.

Figure 2.4. Equilibrium diagram: Aluminium-iron-silicon: metastable condition
Aluminium and silicon form a simple eutectic series with some solid solubility at both ends (Figure 2.5). The eutectic of aluminium and silicon contains 11.7% silicon and freezes at 577°C. The aluminium-rich constituent, under conditions of equilibrium, contains 1.65% silicon at this temperature and the silicon-rich constituent 6.5% aluminium. The solid solubility of silicon in aluminium decreases to 1.3% at 550°C, 0.8 percent at 500°C, 0.29 percent at 400°C and 0.05-0.008% at 250°C.

Two forms of silicon can exist in the alloys:
1. that resulting from precipitation from a solid solution and
2. that produced by direct solidification from the eutectic melt.

The two are crystallographically equivalent but differ in form and distribution. There are no intermetallic compounds between aluminium and silicon. (King, F 1987)
Effect of iron

Iron is virtually insoluble in these alloys and occurs as the ternary compound $\beta$ (FeSi). If the iron is less than 0.6%, the compound occurs as small needles and plates in the eutectic, at a rather higher value it occurs in massive form causing brittleness and so called coarse crystalline fracture, leading to a very marked deterioration in the mechanical properties.

2.4.3 5XXX GROUPS (ALUMINIUM-MAGNESIUM ALLOYS)

The aluminium rich binary aluminium-magnesium alloys form a eutectic ferrous series with appreciable solid solubility at the aluminium end. The eutectic of which the second constituent is that designated $\beta$ or Mg2Al3 lies at 35 percent Mg and 450°C. (Figure 2.6) (King, F. 1987). The aluminium rich solid solution contains 15.35% magnesium at the eutectic temperature, falling to 11.8% at 400°C, 5% at 300°C, 4% at 200°C and about 2% at 100°C. This fall in solubility is accompanied by the rejection of Mg2Al3 from the $\alpha$ solid solution. For precipitation of $\beta$, the alloy must be treated at a temperature of 200°-300°C and the time of treatment is dependent upon the exact temperature level. The precipitation may be continuous or discontinuous, depending upon the tempering temperature used; discontinuous precipitation is accompanied by the formation of a new solid solution, whereas continuous precipitation generates a Widmanstätten structure (needles of constituent precipitation in three crystallographic directions), the scale of which decreases as the tempering temperature is raised. Equilibrium is seldom attained during solidification. It is not uncommon for those portions of the liquid that are last to solidify to become so enriched with magnesium that the eutectic composition is reached and $\beta$ may appear as a constituent in commercial alloys having a magnesium content of the order of 3-4 percent when solidified rapidly. (King, F. 1987)
Precipitation in aluminium-magnesium-silicon alloys

In the alloy systems, aluminium-magnesium-silicon, precipitation is considered as an indication of lattice hardening but in the case of aluminium-magnesium alloys age-softening takes place because of the large particle size instead of fine dispersion of the precipitate.

The effect of impurities:

The two most common impurities in aluminium-magnesium alloys are silicon and iron. The former combines with magnesium to form the binary compound Mg₂Si and this can often be seen in microsections as small particles, grey or blue in colour. Silicon combines preferentially in this manner, so that little is available for the formation of other silicides. Consequently iron, when present as an impurity, tends to occur as FeAl₂ in preference to the ternary compounds α(Fe₃Si) and β(Fe₃Si).
2.4.4 6XXX GROUP (ALUMINIUM – MAGNESIUM-SILICON ALLOYS)

The equilibriums diagrams of the ternary aluminium-magnesium-silicon liquidus surface is shown in figure 2.7, the solidus in figure 2.8 and the limits of solubility in figure 2.9. (King, F. 1987)

Aluminium and the binary constituent Mg,Si form a quasi-binary system dividing the ternary system into two parts. In the quasi-binary system the two constituents form a eutectic at 595°C containing 8.15 per cent Si and there is appreciable solid solubility at the aluminium end reaching 0.85 per cent Mg, 1.10 per cent Si at the eutectic temperature, both partial ternary systems are eutectiferous. Aluminium, silicon and Mg,Si form a ternary eutectic containing 4.97 per cent magnesium, 12.95 per cent magnesium, 12.95 per cent silicon and freezing at 555°C while aluminium, Mg,Al form one at 33.2 per cent magnesium, 0.37 per cent silicon, freezing at 451°C. The primary Mg,Si field is ridge-shaped. (King, F. 1987).

![Figure 2.7: Aluminium-magnesium-silicon liquidus](image)

The single-phase field, over which aluminium is the only constituent to solidify, terminates at 15.3 per cent magnesium and 0.1 per cent silicon at 415°C.
Limits of solid solubility

A knowledge of the limits of solid solubility in this alloy system is of very great importance because the wide range of solubility along the quasi-binary line, and marked decrease in solid solubility with temperature renders these alloys susceptible to heat treatment for the improvement of mechanical properties. It is therefore essential to know how the relationships are affected by an excess of magnesium or silicon over that required to form Mg$_2$Si.

In the Fig. 2.9 isothermals have been inserted at intervals of 10°C. On the silicon side of the quasi-binary line, the apex of the three-phase triangle (Al+ Mg$_2$Si+Si) moves towards the aluminium corner with falling temperature, so that the range of compositions over which both constituents are deposited from solid solution widens as the temperature is reduced, and at 300°C extends almost to the quasi-binary line; the isothermals move closer together and approach the aluminium-magnesium face of the model. The solubility of Mg$_2$Si falls off very rapidly in the presence of magnesium over that required to form Mg$_2$Si. (King, F. 1987).

The reaction between magnesium and silicon is a balanced one, requiring an excess of either magnesium or silicon for its completion. It is possible, therefore, for true silicon to appear as a micro constituent in alloys, the composition of which lie along the quasi-binary line, or which contain a small excess of magnesium. The maximum divergence from the quasi-binary equilibrium occurs at about 1.2 per cent silicon where an excess of some 2 per cent magnesium is needed to suppress completely the silicon.

Mg$_2$Si phase

Under the conditions of equilibrium, in alloys containing an excess of silicon, Mg$_2$Si does not appear as a constituent of the eutectic until a magnesium content of about 0.8 per cent has been reached, but the aluminium-rich phase is incapable of reaching saturation during commercial conditions of casting, with the result that Mg$_2$Si appears at as little as 0.2 per cent magnesium. The Mg$_2$Si crystallizes in the anti-fluorite system the magnesium particles
occupy the fluorine sites, giving a simple cubic distribution while the cube centres are alternately empty (holes) and occupied by a silicon particle or atom. (King, P. 1987)

The 'holes' in Mg$_2$Si differ from the vacancies that can exist in the lattice and from those present in an aluminium after heating and quenching. It can therefore be expected that there will be formed zones and precipitates or Guinier-Preston compounds near any dislocations present or formed by clustering of vacancies. Thermodynamic analysis of binary aluminium-magnesium and aluminium-silicon systems shows repulsion of aluminium-magnesium and attraction of aluminium-silicon. The precipitates or zones can thus be coherent with the matrix and produce hardening in the latter by partial coherency stressing and by dispersion.

Figure 2.8: Aluminium-Magnesium-Silicon solidus
Quenching aluminium-magnesium-silicon commercial alloys from high temperatures produces a supersaturated solution of magnesium and silicon in a aluminium but clusters survive since that attraction between magnesium and silicon is so high. Some of the vacancies and dislocation loops are simultaneously frozen in. On tempering at around 175°C the vacancies and solute atoms migrate towards the dislocation loops (or spirals) to form clusters, zones and Mg$_2$Si precipitates. The hardening obtained after quenching and tempering is due to the dispersion of Mg$_2$Si in $\alpha$, while $\alpha$ itself is hardened by the excess of silicon or magnesium compared with the stoichiometric Mg$_2$Si ratio.

![Figure 2.9 Aluminium-Magnesium-Silicon: Limits of Solubility](image-url)
## 2.5 ALUMINIUM WELDING

The principal processes used for the joining of aluminium are listed in Table 2.2 (www.weldengineer.com).

Table 2.2: Principal processes used for the joining of aluminium

<table>
<thead>
<tr>
<th>Process</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion welding</td>
<td>High-quality, all position welding process that utilises a non-consumable electrode; may be used with or without wire additions; may be manual, mechanised or fully automated; low deposition rate, higher with hot wire additions; straight or pulsed current.</td>
</tr>
<tr>
<td>Tungsten inert gas</td>
<td>High-quality, all position welding process that utilises a continuously fed wire; may be manual, mechanised or fully automated; can be high deposition rate; twin wire additions; straight or pulsed current.</td>
</tr>
<tr>
<td>Metallic arc inert gas</td>
<td>Limited application; uses a flux-coated consumable electrode; non- or lightly stressed joints; obsolete.</td>
</tr>
<tr>
<td>Oxy-gas</td>
<td>Low-quality weld metal, unstressed joints; obsolete.</td>
</tr>
<tr>
<td>Electron beam welding</td>
<td>High-quality, precision welding; aerospace/defence and electronic equipment; high capital cost; vacuum chamber required.</td>
</tr>
<tr>
<td>Laser welding</td>
<td>High-quality, precision welding; aerospace/defence and electronic equipment; high capital cost.</td>
</tr>
<tr>
<td>Electro-gas, electro-slag, submerged arc</td>
<td>Limited applications, e.g. large bus bars, porosity problems, largely obsolete.</td>
</tr>
</tbody>
</table>
Welding with fusion and pressure

Magnetically impelled arc butt welding
Butt joints in pipe; capital equipment required but lower cost than flash butt; fully automated.

Resistance and flash welding
Spot, projection spot seam welding
Lap joints in sheet metal work, automotive, hollowware, aerospace industry; high capital cost; high productivity.

Weld bonding
Combination of spot welding through an adhesively bonded lap joint; automotive industry; very good fatigue strength.

Solid phase bonding
Friction welding
Butt joints in round and rectangular bar and hollow sections; flat plate and rolled section butt welds (friction stir), dissimilar metal joints; capital equipment required.

Explosive welding
Field pipeline joints, dissimilar metal joints, surfacing

Ultrasonic welding
Lap joints in foil; thin to thick sections, Al-Cu joints for electrical terminations.

Cold pressure welding
Lap and butt joints, e.g. Al-Cu, Al-sheet and wire.

Hot pressure welding
Roll bonded lap joints, edge to edge butt joints.

The most frequently used joining process for aluminium is Tungsten Inert Gas welding (TIG) also known as Gas Tungsten Arc Welding (GTAW). Many other processes, of course, can join aluminum, but in the lighter gauges the most applicable process is TIG. (www.lincolnelectric.com/knowledge/articles/content/tigalum.asp) The popularity of aluminum in automotive applications has brought TIG welding to a new golden age. Mechanically strong and visually appealing, TIG welding is the number one process chosen by professional welders for professional racing teams, and the avid auto enthusiast or hobbyist.
2.6 TIG WELDING

The TIG process uses a tungsten electrode enclosed inside a gas-shielded electrode holder to create a welding arc. The holders have an insulated handle and attached to the electrical power supply and shielding gas which flows through the torch, protecting the tungsten electrode and the work from oxidation. The tungsten inside the holder does not melt. It is essentially a permanent but replaceable part of the TIG torch. Filler metals, when used, are fed into the arc produced between the tungsten electrode and the work piece. When filler metals are used, torch is held in one hand and the bare filler metal rod is fed into the arc and molten weld puddle with the other. (Figure 2.10)

Figure 2.10. Tungsten Inert Gas Welding (www.weldengineer.com/Aluminium.htm)

Because in gas tungsten-arc welding the heat is produced between the electrode and the work, edges of the work pieces are melted and are joined as the weld puddle solidifies.

To obtain welds of good quality by the gas-tungsten arc process, it is essential that all surfaces to be welded and adjacent areas be clean. Filler metal, if used must be clean. Further it is essential that the components of the assembly being welded be held firmly in the correct position relative to one another. Fixturing is necessary when fit-up is marginal, work metals are thin, shapes are complex, welding is done without filler metal or automatic welding is used.
2.6.1 EQUIPMENT

The basic system includes a gas supply, a gas regulator, a power supply, and the torch. There are three basic power supplies used in the TIG welding process. They are direct current straight polarity (DCSP) power supply, the direct current reverse polarity (DCRP) power supply and the alternating current high frequency (ACHF) modified power supply. In the DCSP power supply, the tungsten electrode is negative or cathode, and the base metal is positive or the anode. (figure 2.11) The electron flow is from the cathode to the anode. Because of the direction of this flow, two-thirds of the total heat in the arc column is released in the base metal. The tungsten electrode can be of

![Diagram of TIG welding with DCSP](www.ekworldwide.com)

Figure 2.11: TIG welding with DCSP (www.ekworldwide.com)

a very small diameter because the tungsten will not receive the major portion of the heat. It can have a smaller mass to dissipate the heat that it does absorb. The DCSP power supply does not perform any cleaning action, the base metal must therefore, be clean in order to use DCSP.

In DCRP power supply, the electron flow is from the base metal to the electrode. Because of this electron flow to the tungsten electrode, approximately two-thirds of the heat generated by the arc column is absorbed by the tungsten electrode. The electrode therefore has to be a larger
mass. (figure 2.12) The electrons that leave the base metal and are accelerated to the electrode carry with them some of the oxides from the base metal. The cleansing of the surface results from the bombardment of the surface by the positively charged ions.

Alternating current is also used as power supply for tungsten inert gas welding. In AC supplies the current value is essentially zero at the instant when the current reverses its direction. At this point the arc is extinguished and thus the arc column that is established is unstable and erratic. With a high frequency generator in the system a more even current flow is possible. This stabilizes the arc. (figure 2.13)
The electron flow determines the penetration patterns in DCSP, DCRP and ACHF welding. The penetration of DCSP is narrow and deep because the electrons impinge on the base metal. In DCRP, on the other hand, the electron flow is from the base metal to the electrode and the major portion of the heat is absorbed by the electrode; therefore, the weld bead is relatively shallow and wide. (Kurny, 2002)

2.6.2 ARC INITIATION:

Some preliminary means of initiating emission of electrons and ionisation of the gas is generally used for initiating (striking) the arc. Energy for this emission and ionisation can be obtained by touching the energized electrode to the work and quickly withdrawing it to the desired arc length.

2.6.3 ELECTRODE AND FILLER METAL POSITIONS

Once the arc is started the torch is held so that the electrode is positioned at an angle of about 75° to the surface of the workpiece and points in the direction of welding, as shown in all views in figure 2.14. To start welding the arc usually is moved in a circular fashion until enough base metal melts to produce a weld puddle of suitable size (Figure 2.14(a)). As adequate fusion is achieved, the weld is made by gradually moving the electrode along the adjoining edges of the parts to be welded, so as progressively to fuse the parts together (Figure 2.14(b)). Filler metal, when added manually, is often held at an angle of about 15° to the surface of the work and is slowly fed into the weld puddle (Figure 2.14(c)). Filler metal must be fed carefully, to avoid disturbing the gas shield or touching the electrode and thereby causing oxidation at the end of the filler rod or contamination of the electrode. (Metals Handbook, volume 6, 1979).
Figure 2.14: Position of torch and filler metal in manual gas tungsten arc welding.

To stop welding, first the filler metal is withdrawn from the puddle (Figure 2.14(d)), but is momentarily kept under the gas shield to prevent oxidation of the filler metal, then the torch is moved to the leading edge of the puddle (Figure 2.14(e)) before the arc is extinguished. The arc can be extinguished by raising the torch just enough to extinguish the arc, but not enough to cause contamination of the weld crater and the electrode.

2.6.4 ARC LENGTH

Arc length equal to about 1.5 times the electrode diameter is used in many applications of gas-tungsten arc welding, but it may vary for several specific applications. The greater the arc length, the higher is the heat dissipation into the surrounding atmosphere. Also, long arcs ordinarily interfere, to an extent, with steady progression of the weld.

2.6.5 ELECTRODES

The use of a non-consumable electrode that is, an electrode that does not supply filler metal constitutes the major difference between gas tungsten arc welding and other metal-arc welding processes.

Tungsten, which has the highest melting temperature of all metals (3410 C, or 6170F), has proved to be the best material for nonconsumable electrodes. In addition to having extremely high melting point, tungsten is a strong emitter of electrons, which stream across the arc path, ionize it and thus facilitate the maintenance of a stable arc (Welding Handbook, 1993).
Tungsten of commercial purity (99.5% W) and tungsten alloyed with either thorium or zirconium are the electrode materials used in virtually all applications of gas tungsten-arc welding. Pure tungsten electrodes cost about 25 to 35% less than the thoriated types, depending on finish.

Electrodes having seams, cracks, pipes, or nonmetallic segregated inclusions should not be used. Any of these structural imperfections will substantially reduce the maximum current density that the electrode will tolerate. Also, irregularity on the surface of the electrode may cause the arc stream to "backfire" and attach itself to the electrode at some distance back from the tip, this results in a welding difficulty that need not have occurred. Electrodes should be stored in a clean container until they are needed. Grease or dirt on the surface of tungsten electrodes will interfere with good electrical contact when they are inserted into the torch through arcing to the collet. Also, dirty electrodes can contaminate the weld metal while welding is in progress. Generally the electrode size should be chosen so that the electrode will operate at near-maximum current-carrying capacity. At such a current level, the heat of the arc is more concentrated. This ensures maximum penetration, a stable arc, high welding speed, and minimum width and convexity of weld bead. The electrode size must be chosen for the current required and the speed desired for the specific application.

2.6.6 TUNGSTEN CONTAMINATION OF WELD PUDDLE.

When a pure tungsten electrode strikes the weld puddle, tungsten will be deposited in the weld metal. Because the contaminating tungsten may impair the strength and corrosion resistance of the welded joint, if the weldment is critical the welding operation should be stopped when such a strike has been made, and the tungsten should be mechanically routed out of the weld.

To remove the tungsten inclusions, carbide burrs can be used, an ordinary grinding wheel is likely to push the embedded particles even farther into the work as the wheel goes down into the material. For critical weldments, it may be necessary to radiograph the area to ascertain that all of the tungsten has been routed out before resuming welding. Tungsten particles show up as white spots in weld radiographs. (Metals Handbook, volume 6, 1979).
2.6.7 CONTAMINATION OF TUNGSTEN ELECTRODES

During welding, the tip of a pure tungsten electrode reaches a temperature of at least 6200 F, which is above the melting point. Any filler metal or base metal that strikes the molten tip is vaporized to a degree. It also chills the molten tip enough so that the tungsten will combine with the filler or base metal to form an alloy. If welding is continued, the arc will be wild and unstable. When this occurs, there are two alternatives: (a) to break off the contaminated section of electrode and start welding with a clean section, or (b) to hold the arc on a section of copper or other material until the electrode has been cleared of contaminating metal through its vaporization. It can be seen through the filter lens that at the instant of clearing, the arc will stabilize itself and regain a normal welding condition.

The contamination of tungsten electrodes results not only in defacing of the work piece, but also in loss of several minutes of welding time while the electrode is being cleared of the base metal plated on its surface or alloyed with it. (Metals Handbook, volume 6, 1979) When the electrode is being used at or near its maximum current capacity, if the torch is given a quick flip instantly after the electrode strikes the base metal or filler metal, most of the contaminating metal will slide down and off the end of the electrode. However, it may still be necessary to hold the arc for a short time on a piece of copper or other material, in order to clean the electrode completely. A considerable amount of electrode can be saved by this technique.

2.6.8 SHIELDING GASES

The main requirement of a shielding gas is that it excludes air from the weld puddle, the electrode, and the heated end of the filler rod (if used), to avoid contamination of the weld deposit. Shielding gas does not directly add heat to the weld. The gases ordinarily used in gas tungsten-arc welding are Argon, Helium, Argon-helium mixtures, Argon-hydrogen mixtures. The choice of shielding gas can significantly affect weld quality as well as welding speed. Argon, helium, and argon-helium mixtures will not react with tungsten or tungsten alloy electrodes and have no adverse effect on the quality of the weld metal. (Metals Handbook, volume 6, 1979).
2.7 FILLER ALLOY SELECTION FOR ALUMINUM WELDING

The selection of the correct filler alloy is a major factor in the successful welding of aluminum, and essential for the development and qualification of suitable welding procedure specifications. Unlike steel, where a filler alloy is usually matched with the tensile strength of the base alloy alone, typically it is possible to weld many of the aluminum base alloys with any one of a number of filler alloys. There are usually a number of filler alloys that will meet or exceed the tensile strength of the base material in the as-welded condition. However, the selection of filler alloy is typically not only based on the tensile strength of the completed weld.

There are a number of variables that need to be considered during the selection of the most suitable filler alloy for a particular base alloy and component operating condition. When choosing the optimum filler alloy, both base alloy and desired performance of the weldment must be of prime consideration. Each of the variables should be examined which are need to consider prior to the final selection of the most suitable filler alloy for a particular application. (www.alcotec.com/attsw.htm)

2.7.1 EASE OF WELDING OR RELATIVE CRACK SENSITIVITY

This is based on the filler alloy / base alloy combination and its relative crack sensitivity. It is necessary to look at the crack sensitivity curves which are used to assess hot cracking sensitivity for the different filler alloy / base alloy chemistry combinations.

Hot cracking is typically a result of a metallurgical weakness of the weld metal as it solidifies and transverse stress across the weld. The metallurgical weakness may result from the wrong filler alloy / base alloy mixture, and the transverse stress from shrinkage during
solidification of the weld. These cracks are called hot cracks because they occur at temperatures close to the solidification temperature.

To minimize the risk of hot cracking (causing due to wrong filler alloy selection) two issues can be considered, the reduction of transverse stresses across the weld and the avoidance of critical chemistry ranges in the weld.

2.7.2 THE REDUCTION OF STRESSES:

Lower melting & solidification point:

For base alloys with a high susceptibility to hot cracking such as many of the 2xxx series alloys, a 4xxx series filler such as 4145 that has an extremely low solidification temperature (970°F) can be used. (www.alcontec.com/articles.htm)

This low solidification temperature of the filler alloy ensures that the 4145 weld is the last area to solidify and thereby allows the base material to completely solidify and reach its maximum strength before stresses are applied to it by the solidification / shrinkage stresses of the weld.

Smaller freezing temperature range: By using filler alloy such as 4047, which has a freezing range of around 10°F weds can be made which solidify quickly. This provides less time for liquid metal to be subjected to shrinkage stresses during the solidification process.

Critical chemistry ranges

This issue is best addressed by use of the relative crack sensitivity curves as seen in Figure 2.15. The chart shows the crack sensitivity curves for the most common weld metal chemistries developed during the welding of the structural base alloy materials.
1. The aluminum, silicon alloys (4xxx series) are found as non-heat treatable, and heat treatable alloys with 4.5 to 13% silicon are used predominately for filler alloys. Silicon in an aluminum filler alloy / base alloy mixture, of between 0.5 to 2.0% produces a weld metal composition which is crack sensitive. A weld with this chemistry will usually crack during solidification. Care must be exercised if welding a 1xxx series (pure Al) base alloy with a 4xxx series (Al – Si) filler alloy, to prevent a weld metal chemistry mixture within this crack sensitive range.

2. The aluminum, copper alloys (2xxx series) are heat treatable high-strength materials often used in specialized applications. As can be seen from the chart, they exhibit a wide range of crack sensitivity. Some of these base alloys are considered poor for arc welding because of their sensitivity to hot cracking, but others are easily welded using the correct filler alloy and procedure.
3. The aluminum-magnesium alloys (5xxx series) have the highest strengths of the non-heat treatable aluminum alloys, and for this reason are very important for structural applications. Magnesium in an aluminum weld, from 0.5 up to 3.0%, produces a weld metal composition which is crack sensitive. Another issue relating to these base alloys, which is not directly related to the crack sensitivity chart but is a very important factor for filler alloy selection, must be addressed. As a rule the Al-Mg base alloys with less than 2.8% Mg content can be welded with either the Al-Si (4xxx series) or the Al-Mg (5xxx series) filler alloys dependent on weld performance requirements. The Al-Mg base alloys with more than about 2.8% Mg typically cannot be successfully welded with the Al-Si (4xxx series) filler alloys. This is due to a eutectic problem associated with excessive amounts of magnesium silicide Mg2Si developing in the weld structure, decreasing ductility and increasing crack sensitivity.

4. The aluminum-magnesium-silicon alloys (6xxx series) are heat treatable. The 6xxx series base alloys, typically containing around 1.0% magnesium silicide Mg2Si, cannot be welded successfully without filler alloy. These alloys can be welded with 4xxx series (Al-Si) or 5xxx series (Al-Mg) filler alloys dependent on weld performance requirements. The main consideration is to adequately dilute the Mg2Si percentage in the base material with sufficient filler alloy to reduce weld metal crack sensitivity.

2.7.3 WELD STRENGTH

Tensile strength of groove welds, and shear strength of fillet welds should be examined to see the filler alloy effect on these properties.

Groove Weld Tensile Strength: Typically the HAZ of the groove weld dictates the strength of the joint and often many filler alloys can satisfy this strength requirement. However, there are factors to consider when developing welding procedures for the non-heat treatable and the heat treatable alloys.
1. For non-heat treatable alloys, the area adjacent to the weld will be completely annealed. These alloys are annealed by heating to 600-700°F, and the required time at this temperature is short. The welding procedure will have little effect upon the transverse ultimate tensile strength of the groove weld as the annealed HAZ will typically be the weakest area of the joint. Welding procedure qualification for these alloys is based on the minimum tensile strength of the base alloy in its annealed condition.

2. The heat treatable alloys require longer times at temperature to fully reduce their strength. This does not typically occur during welding and the strength of the HAZ will only be partially reduced. The amount of strength loss is both time and temperature related in these alloys. The faster the welding process and heat dissipation from the weld area, the less the heat effect and higher the as-welded strength. Excessive preheating, lack of interpass cooling, and excessive heat input from slow, weaving weld passes all increase peak temperature. These factors by themselves, as well as the use of too small a specimen to provide adequate heat sink, can create sufficient overheating so that minimum strength values required to pass procedure qualification tests are not met.

Fillet Weld Shear Strength

Unlike groove welds, fillet weld strength is largely dependent on the composition of the filler alloy used to weld the joint. The joint strength of fillet welds is based on shear strength which can be affected considerably by filler alloy selection. In structural applications the selection between 5xxx series filler or a 4xxx series filler may not be so significant with regard to tensile strength of groove welds. However, this may not be the case when considering the shear strength of fillet welds.

Typically the 4xxx series filler alloys have lower ductility and provide less shear strength in fillet-welded joints. The 5xxx series fillers typically have more ductility and can provide close to twice the shear strength of a 4xxx series filler alloy in some circumstances. Tests have shown that a required shear strength value in a fillet weld in 6061 base alloy required a 1/4 inch fillet weld with 5556 filler compared to a 7/16 inch fillet with 4043 filler alloy to
meet the same required shear strength. This can mean the difference between a one run fillet and a three run fillet to achieve the same strength.

2.7.4 WELD DUCTILITY

The effect of filler alloys on the ductility of the completed weld, its influence on weld performance, and testing methods used for welding procedure qualifications should be examined.

Ductility is a property that describes the ability of a material to plastically flow before fracturing. Fracture characteristics are described in terms of ability to undergo elastic stretching and plastic deformation in the presence of stress raisers (weld discontinuities). Increased ductility ratings for a filler alloy, indicate greater ability to deform plastically and to redistribute load, and thereby decrease the crack propagation sensitivity. Ductility may be a consideration if forming is to be performed after welding or if the weld is going to be subjected to impact loading. Also ductility is considered when conducting bend tests during procedure qualifications. The 4xxx series filler alloys have relatively low ductility, this is addressed with special requirements within the code or standard relating to test sample thickness, bending radius, and/or material condition.

2.7.5 CORROSION RESISTANCE

The use of SMAW electrodes with their flux coating gave concern for possible corrosion problems relating to entrapped flux within the welded joint. Today almost all aluminum welding is performed using the GMAW (MIG) or the GTAW (TIG) welding processes, and flux entrapment is not an issue. One filler alloy, developed primarily for use within a specific corrosive environment, is filler alloy 5654 developed to weld storage tanks to hold hydrogen peroxide. This filler alloy has a high purity with low copper and manganese content which is required for this very active chemical. Most unprotected aluminum base alloy - filler alloy combinations are quite satisfactory for general exposure to the atmosphere. In cases where a dissimilar aluminum alloy combination of base and filler is used, and electrolyte is present, it is possible to set up a galvanic action between the dissimilar compositions. The difference in
alloy performance can vary based upon the type of exposure. Filler alloy charts ratings are typically based on fresh and salt water only. Corrosion resistance can be a complex subject when looking at service in specialized high corrosive environments, and may necessitate consultation with engineers from within this specialized field.

2.7.6 SERVICE TEMPERATURE

The importance of filler alloy selection for components used at temperatures above 150°F, and the consequences of the incorrect selection of filler alloys for these service conditions should be considered. Stress corrosion cracking is an undesirable condition which can result in premature failure of a welded component. One condition which can assist in the development of this phenomenon is Magnesium segregation at the grain boundaries of the material. This condition can be developed in the Mg alloys of over 3 % through the exposure to elevated temperature. When considering service at temperatures above 150°F, the use of filler alloys which can operate at these temperatures without any undesirable effects to the welded joint must be considered. Filler alloys 5356, 5183, 5654 and 5556 all contain in excess of 3 % Mg, typically around 5%. Therefore, they are not suitable for temperature service. Alloy 5554 has less than 3 % Mg and was developed for high temperature applications. Alloy 5554 is used for welding of 5454 base alloy which is also used for these high temp applications. The Al – Si (4xxx series) filler alloys may be used for some service temperature applications dependent on weld performance requirements.

2.7.7 COLOR MATCH AFTER ANODIZING

This may be a major consideration for anodized aluminum used in cosmetic applications. The color of an aluminum alloy when anodized depends on its composition. Silicon in aluminum causes a darkening of the alloy when chemically treated during the anodizing process. If 5% silicon alloy 4043 filler is used to weld 5061, and the welded assembly is anodized, the weld becomes black and is very apparent. A similar weld in 6061 with 5356 filler dose not discolor during anodizing, so a good color match is obtained.
Filler alloy selection can be significantly influenced with the requirement for thermal post weld heat treatment. The need for a filler alloy that will respond to heat treatment may be the only way to obtain required mechanical properties.

Typically, the common heat treatable base alloys, such as 6061-T6, lose a substantial proportion of their mechanical strength after welding. Alloy 6061-T6 has typically 45,000 PSI tensile strength prior to welding and typically 27,000 PSI in the as-welded condition. Consequently, on occasion it is desirable to perform post weld heat treatment to return the mechanical strength to the manufactured component. If post weld heat treatment is the option, it is necessary to evaluate the filler alloy used with regards to its ability to respond to the heat treatment. Most of the commonly used filler alloys will not respond to post weld heat treatment without substantial dilution with the heat treatable base alloy. This is not always easy to achieve and can be difficult to control consistently. For this reason, there are some special filler alloys which have been developed to provide a heat treatable filler alloy which guarantees that the weld will respond to the heat treatment. Filler alloy 4643 was developed for welding the 6xxx series base alloys and developing high mechanical properties in the post weld heat-treated condition. This filler alloy was developed by taking the well-known alloy 4043 and reducing the silicon and adding 0.10 to 0.30 % magnesium. This chemistry introduces Mg,Si into the weld metal and provides a weld that will respond to heat treatment.

Filler alloy 5180 was developed for welding the 7xxx series base alloys. It falls within the Al-Zn-Mg alloy family and responds to post weld thermal treatments. It provides very high weld mechanical properties in the post weld heat-treated condition. Other heat treatable filler alloys have been developed including 2319, 4009, 4010, 4145, 2060, A356.0, A357.0, C355.0 and 357.0 for the welding of heat treatable wrought and cast aluminum alloys.

It must be concluded that final determination of the most suitable filler alloy can only be made after a full analysis of the welded components performance requirements. Filler alloy selection for welding aluminum is an essential part of the development and qualification of a successful welding procedure qualification.
2.8 ALUMINIUM WELDING METALLURGY

Ideally a weldment by this is meant the complete joint comprising the weld metal, heat affected zones (HAZ) and the adjacent parent metal should have the same properties as the parent metal. There are, however, a number of problems associated with the welding of aluminium and its alloys that make it difficult to achieve this ideal. The features and defects that may contribute to the loss of properties comprise the following:

- Gas porosity.
- Oxide inclusions and oxide filming.
- Solidification (hot) cracking or hot tearing.
- Reduced strength in the weld and HAZ.
- Lack of fusion
- Reduced corrosion resistance
- Reduced electrical resistance

2.8.1 Porosity in aluminium and its alloys

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.

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 figure 2.16. 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.

Porosity tends to be lowest in autogenous welds. When filler metal is used porosity levels tend to increase because of contamination from the wire. Of the conventional fusion welding processes TIG has lower levels of porosity than MIG due to this hydrogen contamination of the wire (Lancaster, J.F., 1980). Increasing the arc current increases the temperature of the weld pool and thereby increases the rate of absorption of hydrogen in the molten metal.
Conversely, in the flat welding position increasing the heat input can reduce porosity when the rate of gas evolution from the weld exceeds the rate of absorption, slowing the rate at which the weld freezes and allowing the hydrogen to bubble out of the weld. A similar effect can be achieved by reducing the travel speed, increasing arc voltage and or arc length increases the exposure of the molten metal to contamination and porosity will thereby increase. The alloy composition can also influence the amount of porosity by changing the solubility of hydrogen-magnesium in particular has a beneficial effect. It is thought that magnesium raises the solubility and reduces absorption of hydrogen by as much as twice at 6% Mg. Copper and silicon have the opposite effect. A conclusion that can be drawn from this is that when porosity is encountered the use of Al-Mg filler can assist in reducing the problem. This assumes of course that such filler metal is acceptable to the specific application.

Figure 2.16: Solubility of hydrogen in aluminium
The sources of hydrogen are many and varied but one of the primary sources is the welding consumables. Moisture is an intrinsic part of the flux in any of the flux shielded processes such as manual metallic arc (MMA) or SMA (shielded metal arc), and submerged arc (SA) welding. During welding this moisture decomposes in the arc to give hydrogen, resulting in a large amount of porosity. This is one reason why these processes are not widely used to weld aluminium.

The gas used in the gas shielded processes is another source of moisture which is easy to overlook. Ideally gas with a dew point of less than -50°C (39 ppm water) should be used. To achieve such a high purity it is essential to purchase the gas with a guaranteed low dew point. It is also necessary to ensure that when it is delivered to the weld pool it has maintained this high degree of purity. This means that the gas supply system should be checked at regular intervals for leaks, that damaged hoses are replaced immediately and joints are sound. When faced with a porosity problem the gas purity should be checked first of all at the torch nozzle before working back along the gas delivery system in a logical manner to locate the source of contamination.

TIG welding wire should be cleaned with a lint-free cloth and a good degreasant before use. Once the wire has been cleaned the wire should not be handled with bare hands but with a clean pair of gloves. The wire should be stored in clean conditions and weld within a short time of cleaning. For the MIG process there are devices available that can be fitted around the wire where it enters the torch liner in the wire feed unit and that will clean the wire as it passes through.

Cleanliness of the parent metal is also extremely important in achieving low levels of porosity— it cannot be emphasized too strongly how important this is. Thorough degreasing is essential, followed by a mechanical cleaning such as stainless steel wire brushing to remove the oxide layer which may be hydrated. Once degreased and wire brushed the parent material should be welded within a short period of time, a period of four hours frequently being regarded as acceptable.

A last source of porosity may be hydrogen dissolved within the aluminium. Although solubility of hydrogen is low in the solid phase there can be sufficient in the parent metal to give a problem on welding. This is unlikely in wrought products but may arise when welding castings or sintered products. (Mathers, G.)
2.8.2 Oxide film removal during welding

Aluminium oxide (Al₂O₃) is a very tenacious and rapid-forming oxide which gives aluminium its excellent corrosion resistance. Aluminium oxide has a very high melting point, 2060°C compared with the pure metal which melts at 660°C. The oxides of most other metals melt at temperatures at or below that of their metals and during welding will float on top of the weld pool as a molten slag. Heating aluminium to its melting point without dispersing the oxide film will result in a molten pool of aluminium enclosed in a skin of oxide, rather like a rubber toy balloon filled with water. This skin has to be removed by some suitable means. With fluxed processes, soldering, brazing and MMA welding, the flux needs to be very aggressive to dissolve the film. Failure to remove these fluxes on completion can give rise to service failures from corrosion and, in addition to porosity, is a further reason why MMA and SA welding are rarely used.

Fortunately, in gas shielded arc welding there is a phenomenon known as cathodic cleaning which can be employed to give the desired result. When the electrode is connected to the positive pole of the power source and direct current is passed there is a flow of electrons from the work piece to the electrode with ions travelling in the opposite direction and bombarding the work piece surface. This ion bombardment breaks up and disperses the oxide film and permits the weld metal to flow and fuse with the parent metal. The MIG welding process uses only DC electrode positive (DCEP) current, using DC electrode negative (DCEN) results in an unstable arc, erratic metal transfer and poor weld quality. Oxide film removal is therefore an intrinsic part of the MIG process.

TIG welding on the other hand, conventionally uses DCEN, which if used on aluminium can result in poor weld quality. Using DCEP with TIG, however, results in the tungsten electrode overheating as some 60-70% of the heat generated in a TIG welding arc may be produced at the positive pole. (Conventionally a rule of thumb for the heat balance in a TIG arc is regarded as being two-thirds at the positive pole, one-third at the negative pole. This however, varies widely depending upon the shield gas, current, arc length, etc.) This can cause melting of the electrode and bring the welding operation to a premature end. A compromise is therefore reached 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 figure 2.17. TIG welding of aluminium is therefore normally carried out with AC, although there are a couple of techniques that use either DCEP or DCEN.
2.8.3 Hot cracking

Hot cracking is a welding problem that does not occur in pure metals but may be found in certain alloy systems. It is not only confined to the aluminium alloys but is also encountered in steels, nickel and copper alloys. The fundamental mechanism is the same in all of the alloy systems and is a function of how metal alloy systems solidify. As the name suggests, this is a high temperature cracking mechanism which, because of its prevalence, is known by a number of different names—hot cracking, hot fissuring, hot shortness, liquation cracking, center-line cracking or solidification cracking (Figure 2.18).

The addition of alloying elements to a pure metal will cause a change in the freezing temperature of the alloy from that of the pure metal and may, result in a number of different phases— a solid solution, a eutectic and an intermetallic compound, for instance, being produced. These changes of state and the relative proportions of each phase are represented on phase diagrams. The lowest melting point composition of the alloy is known as the eutectic composition which freezes at one specific temperature. The other non-eutectic compositions freeze over a range.
During solidification of a metal the lowest melting point constituents are pushed to the grain boundaries by the solidification fronts as the solid particles grow in size. The first solid to form is a unit cell that acts as a nucleus to which atoms attach themselves, forming dendrites. The dendrite increases in size until such time as it begins to collide with its neighbours that have been nucleating and growing in a similar manner. The point at which this collision takes place becomes the grain boundary. Since almost all alloy systems, except eutectics, solidify over a range of temperatures, it is common sense to expect that the first metal to solidify will be the highest melting/freezing point alloy and the last to the lowest melting point composition, always the eutectic if one has formed. The consequence of this solidification process is that the lowest melting point alloy composition is pushed ahead of the solidifying dendrite until it becomes trapped between the adjacent dendrites, i.e. along the grain boundaries. If the difference in melting point between the low melting point eutectic and the bulk of the metal is sufficiently great then the liquid film along the grain boundaries may part as the metal cools and contracts.

![Figure 2.18: Solidification cracking](image)

In most metals this effect is caused by tramp elements or impurities. Sulphur in steel and nickel alloys is a good example where low melting point sulphide eutectics are formed. In the aluminium alloys, however, it is the deliberately added alloying elements themselves that form a range of eutectics with freezing points substantially lower than the bulk metal. This means that all aluminium alloys are susceptible to this form of cracking, differing only in their degree of susceptibility. Cracking tests have determined what is termed the hot short range, the range of composition within which the alloy has a high risk of hot cracking. The hot short range of the common alloying elements is given in appendix.
These results are produced by performing standard cracking tests. These tests are designed to load the weld transversely under controlled conditions to give cracks, the length of which will be a measure of the crack sensitivity of the specific alloy being tested. This enables the alloys to be ranked in order of sensitivity and characteristics such as the hot short range to be determined.

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 figure 2.15. 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.

As the liquid film thickness increases, the force required to tear the film reduces. The force required for cracking begins to increase, however, once there is sufficient eutectic available that it can begin to flow into and fill any cracks that form. The crack sensitivity therefore drops, the cracks heal themselves and a crack-free structure results. This is a very useful feature when welding alloys that are sensitive to liquation cracking in the HAZ. Figure 2.19 illustrates this graphically.

![Generalised picture of crack sensitivity](Gene Mathers)

**Figure 2.19: Generalised picture of crack sensitivity (Gene Mathers)**
The practical consequence of this is that the crack susceptibility of the weld metal is very sensitive to changes in composition. In very many situations when welding aluminium alloys, the filler metal does not match the parent material. It is most important that this fact is realized and that account is taken of the composition of the resultant weld metal. There are a number of other factors, apart from filler metal and parent metal composition, which affect the weld metal composition. Fit-up of the component parts can affect the amount of dilution in a joint. Dilution being the amount of parent metal dissolved into the weld metal during welding. In the root pass a wide gap will give low dilution, a narrow gap high dilution.

Hot cracking may be eliminated by one or more of the following:

- 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. This small grain size reduces hot cracking tendency.
- Controlling the composition of the weld pool by adding filler metal to produce an alloy that is not in the hot short range.
- Using 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.
- Using the highest welding speed. High speeds reduce the length of time of the weld that is within the hot short temperature range. High welding speeds also reduce the HAZ and consequently the shrinkage stresses across the joint.
- Using high-speed, small-volume multi-run procedures instead of large volume, single run deposits.
- Selecting welding and assembly sequences that minimize restraint and residual stresses.
- Selecting a filler metal with a melting point close to that of the parent metal.

2.8.4 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 heat affected zone (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 the properties of the HAZ will match those of the parent metal.

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 (s). The properties of this weld depend upon the composition, the quality and the grain size of the deposit. These in 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 beads therefore generally have better properties than large weld beads and a higher resistance to hot cracking.

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 (Collins, F.R., 1962) 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. For example, a single pass AC-TIG weld in a 6061 series alloy made with a 4043 filler metal will give an ultimate tensile strength of around 300 N/mm² in the post-weld aged condition, a multi-pass MIG weld made with a 4043 filler will give approximately 230 N/mm². Changing the 4043 filler to a 4643, which contains only 0.2% of magnesium, will improve the strength after post-weld ageing to match that of the auto-genous AC-TIG weld. This is a further example of the importance of the correct selection of filler metals and the control of consistency during welding of the aluminium alloys.

Heat affected zone

As mentioned earlier, alloys in the 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.

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. Thus the annealing heat treatment results in a major loss of strength. The result of this practice is illustrated in Fig. 2.20 which shows a 5 XXX alloy TIG welded.

![Figure 2.20: Effect of welding on strength in cold worked alloy](Gene Mathers, The welding of Aluminium and its alloys)
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 a dissolution of the precipitates in the 2XXX series alloys and a coarsening or over-aging of the precipitates in the 6XXX and 7XXX alloys. These effects are illustrated in Fig. 2.21.

Figure 2.21: Effect of welding on age hardened alloy – as welded

One last comment is the potential for the loss of alloying elements from the weld pool that 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.
2.8.5 Liquation cracking

Liquation cracking occurs in the HAZ, when low melting point films are formed at the grain boundaries. These cannot withstand the contraction stresses generated when the weld metal solidifies and cools. Heat treatable alloys, particularly 6xxx and 7xxx series alloys, are more susceptible to this type of cracking. (Figure 2.22).

![Figure 2.22: Liquation cracking](image)

The risk can be reduced by using a filler metal with a lower melting temperature than the parent metal, for example the 6xxx series alloys are welded with a 4xxx filler metal. However, 4xxx filler metal should not be used to weld high magnesium alloys (such as 5083) as excessive magnesium-silicide may form at the fusion boundary decreasing ductility and increasing crack sensitivity.
Experimental procedure

3.1 Base metal composition and dimensions
In the research work aluminium alloy plates of two different grades were used. The chemical analysis of the aluminium plates were carried out by optical emission spectroscopy (OES) and the results found from OES are listed below (table 3.1) From the OES results it was found that one of the base plates was pure aluminium of 1xxx series while the other plate was Al-Mg alloy of 5xxx series. The pure aluminium plate was named as plate A and the aluminium magnesium alloy plate was named as plate B. Then some work pieces were cut from both base plates to perform TIG welding. Work pieces cut from plate A numbered as 1, 2, 3, 4, 5 and 6 and those cut from plate B numbered as 7, 8 and 9. The work pieces are of 11 mm thick, 35 mm long and 16 mm wide. The edges of the work pieces were prepared for TIG welding.

Table 3.1: Chemical composition of two different grades of aluminium alloys

<table>
<thead>
<tr>
<th>Elements</th>
<th>Plate A Plates 1,2,3,4,5,6</th>
<th>Plate B Plates 7,8,9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>99.1%</td>
<td>94.739%</td>
</tr>
<tr>
<td>Si</td>
<td>0.1128%</td>
<td>0.1584%</td>
</tr>
<tr>
<td>Mg</td>
<td>0.0018%</td>
<td>3.82</td>
</tr>
<tr>
<td>Fe</td>
<td>0.61%</td>
<td>0.34%</td>
</tr>
</tbody>
</table>

3.2 Joint configuration and welding parameters used for TIG welding

A TIG welding machine was used for welding. The plates were rigidly clamped and welded in the flat position using two different filler metals (4043 and 5356) and different current settings (Table 3.1). 1% thoriated tungsten electrode of 2.4 mm diameter was used for welding. The joint configuration used for TIG welding is shown below.
Welding parameters used for TIG welding and filler metal compositions are described in table 3.1 and table 3.2 respectively.

Table 3.1: Welding parameters used for TIG welding

<table>
<thead>
<tr>
<th>Material</th>
<th>Plate No</th>
<th>Filler metal used</th>
<th>Current used (Amp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate A</td>
<td>1</td>
<td></td>
<td>145</td>
</tr>
<tr>
<td>Pure aluminium</td>
<td>2</td>
<td>4043</td>
<td>175</td>
</tr>
<tr>
<td>1xxx series</td>
<td>3</td>
<td></td>
<td>195</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5356</td>
<td>145</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td></td>
<td>195</td>
</tr>
<tr>
<td>Plate B</td>
<td>7</td>
<td>4043</td>
<td>145</td>
</tr>
<tr>
<td>Aluminium -</td>
<td>8</td>
<td></td>
<td>175</td>
</tr>
<tr>
<td>Magnesium alloy</td>
<td>9</td>
<td>5356</td>
<td>175</td>
</tr>
<tr>
<td>5xxx series</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2: Filler metal composition:

<table>
<thead>
<tr>
<th>4043 5% Silicon Aluminium Welding rods</th>
<th>Elements</th>
<th>Si</th>
<th>Cu</th>
<th>Fe</th>
<th>Mg</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Composition</td>
<td>4.5-6.0%</td>
<td>0.30%</td>
<td>0.80%</td>
<td>0.05%</td>
<td>Balance</td>
<td></td>
</tr>
<tr>
<td>5356 5% Magnesium Aluminium Welding rods</td>
<td>Elements</td>
<td>Mg</td>
<td>Cu</td>
<td>Fe</td>
<td>Si</td>
<td>Al</td>
</tr>
<tr>
<td>Typical Composition</td>
<td>4.5-5.5%</td>
<td>0.10%</td>
<td>0.40%</td>
<td>0.25%</td>
<td>Balance</td>
<td></td>
</tr>
</tbody>
</table>
3.3 Non destructive testing

To evaluate the soundness of the welded joint, the following non destructive testing techniques were performed on the welded samples after welding.

**Liquid Penetrant Inspection (PT)**

Penetrant was applied to the precleaned surface of the plates and allowed to remain on the surface for 15 minutes. Then developer was used to indicate the discontinuities. Information about penetrant and developer are shown below:

<table>
<thead>
<tr>
<th>Penetrant</th>
<th>Developer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water washable type, Magnaflux, Spot check, Model No: SKLWP</td>
<td>Magnaflux, Spot check, Model No. SKDS2</td>
</tr>
</tbody>
</table>

**Radiography**

An X-ray machine (Model No. XX82505, China) with 250 kV capacity was used to obtain the micrographs. A voltage of 140 kV and a current of 5 mA were applied for 10 second. The film to focus distance was 700 mm.

3.4 Metallographic analysis

After non destructive testing the samples were etched to reveal the microstructure. Optical metallography was performed on all specimens in the as welded condition. Specimens were longitudinally sectioned and prepared as per the standard metallographic practice. Relevant microstructures at the various locations in the weld zone, HAZ and base metals were made. Two types of etching reagent were used

1. 1% HF acid solution in distilled water to etch the welded samples that used Al-Si filler
2. 75 ml distilled water, 15 ml HF and 10 ml HCl to etch the welded samples that Al-Mg filler
3.5 Mechanical Properties

Several destructive testings such as tensile test, hardness test and impact tests were performed to find out the properties at weld zone, heat affected zone and at base metal.

3.5.1 Tensile test

Tension tests of the welded samples were carried out. Three tensile specimens were tested for each plate. In all cases weld portion was at the centre of the specimen. The dimension of the tensile test specimen is shown in figure 3.2.

![Tensile test specimen](image)

**Figure 3.2: Tensile test specimen**

3.5.2 Hardness test

Microhardness testing was conducted using a knoop microhardness tester with 100 gm load and 10 second duration. Macrohardness testing was also conducted using Rockwell hardness tester with 60 Kg load.

3.5.3 Impact test

The impact properties of the joint are also important in certain applications. In order to evaluate the impact properties, charpy impact test specimens were made. Three types of impact specimens were made from each plate. The arrangement of the specimen for charpy test is shown in figure 3.3(a,b and c). Here the notch angle was 45 – 60 degree.
3.6 Scanning electron microscopy

All the fractured surfaces found from impact tests (fractured surface of HAZ, Weld portion and base metal) and also the polish weld surfaces were observed in SEM. The SEM micrographs were taken as secondary electron images and with backscattered images at around 10 kV. Composition measurements of the elements present were conducted by energy dispersive X-ray analysis (EDX) at 10 kV.
RESULTS AND DISCUSSION

4.1 Introduction

In the research work each of the two different grades (1XXX series and 5XXX series) of aluminium alloy plates were welded with two different types of filler metals (4043 (4XXX series) and 5356 (5XXX series)) and with different current setting.

During welding at different conditions various eutectics, intermetallic compounds and phases formed at different temperature and at different compositions. All of these phases/intermetallic compounds contributed to a change in mechanical properties. From structural evaluation and mechanical tests relationships are to be established between the mechanical properties and weld structures.

4.2 Non Destructive Testing of weld

To determine the weld soundness dye penetrant testing and radiography were performed on the welds. The condition of the sample after dye penetrant test is shown in figure 4.1. This test reveals the presence of porosity (found as black spots on the sample) in the welded portion. Radiographs of the samples are shown in figure 4.2 and this result also indicates the presence of porosity that is marked as white spots.
First of all discussion will be carried out on plates 1, 2, and 3 that were welded with 4043 filler metal and with three different current settings. Then discussion will be made on plates 4, 5, and 6, that were welded with 5356 filler metal and with the same three current settings used for the previous plates. Finally, plates 7, 8, and 9 will be discussed.
4.3 Plates 1, 2 and 3

These plates were welded using 4043 filler metal at three different current setting of 145A, 175A and 195A. After welding micrographs were taken at different locations of the samples such as at weld portion, weld root, heat affected zone and base metals. These micrographs of plate 1,2 and 3 are shown in figure 4.3, 4.7 and 4.8.

4.3.1. Features of the welded samples

Micrographs of plates 1, 2 and 3
Location: Weld Portion
Magnification: 400X

Figure 4.3 (a) : Plate 1
Figure 4.3 (b): Plate 2
Figure 4.3 (c): Plate 3
The micrographs of the weld matrix of these plates show the presence of some secondary phase (Figures 4.3 (a, b, c)). To identify these phases first of all the polished surface of the weld portion of these plates were scanned in SEM. The SE images of these plates (figures 4.4 (a)) again revealed the presence of these secondary phases in the weld matrix. These phases were more prominent in the corresponding BSE image of the plates (figures 4.5(a)). The BSE images (figure 4.5) clearly showed the compositional difference between these lines and the remaining weld matrix. On the other hand the SE image (figure 4.4(b)) and BSE image (figure 4.5(b)) of base plate (pure aluminium plate) show no secondary phase. Also the micrograph of base plate does not show any secondary phase. (figure 4.9). So it can be said that this secondary phase formed during welding.

Secondary and corresponding Backscattered Electron images
Location: Polished weld surface and base plate
Magnification: 800X

Figure 4.4 (a) SE image of plate 1

Figure 4.4 (b): SE image of base plate
Pure aluminium (1xxx series)

Figure 4.5 (a): BSE image of plate 1

Figure 4.5 (b): BSE image of base plate
Pure aluminium (1xxx series)
4.3.2. Identifying the secondary phases

To identify this phase EDX analysis of these phases was performed and the result is shown in figure 4.6(b). The EDX spectra indicates the presence of Al and Si in the secondary phase and corresponding semi quantification analysis determines that the secondary phase consist of 34 percent silicon. Whereas EDX analysis of weld matrix is shown in figure 4.6(a) which indicates the presence of only 5-6 percent of silicon that resembles with the filler alloy composition. On the other hand, the binary aluminium silicon equilibrium diagram shows the formation of aluminium-silicon eutectic mixture at this condition. Thus combining the knowledge of Al-Si binary diagram and the EDX results it can be said that the secondary phase in the micrographs are Aluminium-Silicon eutectic mixture. Here the EDX analysis of the base plate (pure aluminium plate) has been shown in figure 4.6(c).

Quantification results

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Figure 4.6(a): plate 1 (Al-5% Si filler) Weld matrix analysis
Figure 4.6(b): plate 1 (Al-3% Si filler)
Weld particle analysis

Quantification results

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Figure 4.6(c) EDX analysis of pure aluminium plate (lxxx series)

Quantification results

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4.3.3. Characteristics of the eutectic mixture

Looking at the micrograph it is clear that the eutectic mixture is different in distribution, shape and size in different plates. Comparing figure 4.3(a) for plate 1, figure 4.3(b) for plate 2 and figure 4.3(c) for plate 3 it can be inferred that the eutectic mixture increases in size with increasing current content. To find out the reason behind this, it was observed that in plate 1 heat input was the lowest. So during solidification from the welding temperature the eutectic mixture in the weld portion did not get enough time to grow in size or to form a continuous network. But as the current content / heat input increased (plates 2 and 3) the Al-Si eutectic mixture got sufficient time to form and to grow in a continuous network. As a result the micrograph of plate 3 (welded with the highest current setting) show the most organized and large, coarser and continuous eutectic mixture than the other two plates (1 and 2).

It is further revealed that the shape, size and orientation of the eutectic mixture are different not only at different welding conditions at different current settings but also at different weld location of the same plate. In the weld root area (figure 4.7) the eutectic mixture is closely spaced than that in the weld portion (figure 4.3). This is because at the root, heat dissipation rate is faster than other weld portion. During welding, root pass is performed first and during solidification of this root portion heat can dissipate from all sides. So root portion seems to be quenched during solidification. But the following weld passes have slow heat dissipation rate. Because during those passes, root and the base metal are already preheated that slows down the cooling rate. Looking at the micrographs at weld root of plates 1, 2 and 3 it is also revealed that in all cases the eutectic mixture is almost same in size and shape. Because at root portion all plates solidify almost in the same manner, so current content has little influence on the microstructure of the weld root portion.
Micrographs of plates 1, 2 and 3
Location: Weld Root Area
Magnification: 400X

Figure 4.7 (a) Plate 1
Figure 4.7 (b): Plate 2
Figure 4.7 (c): Plate 3
Micrographs of the HAZ of these plates are shown in figure 4.8. Discrete network structures of eutectic mixtures are observed at the heat affected zone and these may be attributed to weld dilution where as micrograph of base plate shows no sign of eutectic mixture (figure 4.9). Similar findings were observed by Huang, C., and Kou, S. (2002). For this dilution some eutectic mixture enters into the base metal which affects the fracture properties of the heat affected zone (Explained later in section 4.4.5).

Micrographs of plates 1, 2 and 3  
Location: Heat Affected Zone and Base Plate  
Magnification: 400X
4.3.4. Relationship between microstructure and hardness values

The change in microstructure with heat input is also supported by the microhardness profiles of these plates. Knoop hardness tests were performed at different locations of these plates and the results are shown in figure 4.10, 4.11 and 4.12.

![Plate 1, Hardness at different locations](image)

From these figures it is seen that hardness of plates 1, 2 and 3, at the weld top and middle portion are not as high as hardness of the root portion. This is because of the high heat dissipation rate of the root portion that results in smaller grain size. And smaller grains show greater hardness than larger grains of weld portion. It is also observed from figures that difference in hardness values between weld top and root portion decreases as the welding current increases which inform that high heat input may cause more dilution in the weld structure.

Figure 4.10: Comparison of microhardness values at different locations of plate 1
Figure 4.11: Comparison of microhardness values at different locations of plate 2

Figure 4.12: Comparison of microhardness values at different locations of plate 3
Now comparing the hardness value of the same portion of the weld region of the three different plates (figures 4.13 (a,b,c)) it is seen that plate 2 and 3 show higher hardness value than plate 1 which was welded with a low current setting. This is true for weld top and weld middle portion. But at the root area all plates have almost the same value. Plate 1 was welded with the lowest current setting and it was seen previously that in this plate the eutectic mixture could not grow in size. This eutectic mixture is mainly responsible for the hardness. On the other hand this eutectic mixture substantially increased in size and got coarser as the current content increased. That is it was largest and coarsest in size in plate 3. This result is reflected in the microhardness profiles where plate 2 and 3 show very high hardness value than plate 1 at weld top and middle portion. But at the weld root, the eutectic mixture was almost same in size and shape for all plates. The microhardness profile at root portion (figure 4.13(c)) thus show the same hardness value for all these three plates.

Figure 4.13 (a) Comparison of microhardness values of weld top portion of plates 1,2 and 3
Comparison of Weld middle portion among plates 1 (145A), 2 (175A) and 3 (195A)
Si filler, Base plate - pure aluminium

Figure 4.13 (b): Comparison of microhardness values of weld middle portion of plates 1, 2 and 3

Comparison of Weld root among plates 1 (145A), 2 (175A) and 3 (195A)
Si filler, Base plate - pure aluminium

Figure 4.13 (c): Comparison of microhardness values of weld root portion of plates 1, 2 and 3
The macrohardness value of these plates are graphically represented below (figure 4.14) and it also exhibit the same trend as the microhardness value. Plate 3 shows the highest hardness in the weld portion which is due to the largest and continuous network of Al-Si eutectic mixture. On the other hand plate 1 and 2 have low hardness value because of the discontinuous and small eutectic mixture that did not find sufficient time to grow.

![Macrohardness values of plates 1,2 and 3](image)

Figure: 4.14: Macrohardness values of plates 1,2 and 3

4.3.5 Relationship between fractographs and mechanical properties

From the impact test results (figure 4.15) it was found that plate 2 and 3 have almost same impact energy and this energy is higher than the impact energy of plate 1 (welded with low current setting). The UTS values show the same trend (figure 4.16) that is UTS values tend to increase with an increase in heat input.
Fractured samples found from impact tests were scanned in the scanning electron microscope. The fractographs of these samples are shown in figure 4.17. It was found previously that size of the eutectic mixture increases with increasing current content. That is, the eutectic mixture is the highest in size and concentration in plate 3 and lowest in size and concentration in plate 1. This change in size of this eutectic mixture changes the local stress system that is revealed in the fractographs (figure 4.17).
Fractographs of plates 1, 2 and 3
Location: Weld Portion, HAZ and Base Plate
Magnification: 1000X

Figure 4.17(a): Plate 1
(notch at weld portion)

Figure 4.17(b): Plate 1
(notch at HAZ)

Figure 4.17(c): Plate 2
(notch at weld portion)

Figure 4.17(d): Plate 2
(notch at HAZ)
All these fractographs show the presence of dimples from microvoid coalescence. It can be said that here microvoids initiate during plastic flow at undissolved secondary phase particles (Al-Si eutectic mixture). Separation at the site of microvoid initiation occurs across a second phase particle or at a particle-matrix interface. As the plastic strain increases, the existing microvoids grow, new microvoids are initiated and eventually the enlarged microvoids grow into close enough proximity so that the thin ridges or membranes separating them rupture and fracture occurs. The resultant fracture surfaces have numerous cuplike depressions or dimples. Dimple size appears to
depend on the number of microvoid-initiation sites available and the relative plasticity of the matrix. The fracture surface of weld portion of plate 3 (welded with the highest current) shows larger microvoid dimples, because plate 3 consists of largest size of eutectic mixture and therefore a small number of initiation sites for microvoids. The fracture surface of base plate of pure aluminium with no microvoid initiation sites exhibits no microvoid coalescence, it shows totally shear fracture. (Figure 4.17 (g)). On the other hand fracture surface of HAZ shows mixed mode of fracture between base and weld portion and as a result always a high impact energy than weld portion, because in the HAZ dilution causes presence of eutectic mixture there. Otherwise the HAZ would have showed the same fractured surface as that of base metal.

4.4 Plates 4, 5 and 6

These plates were welded with 5356 filler metal and with three different current setting. Similarly as plates 1, 2 and 3, here also micrographs were taken at different locations of the samples such as at weld portion, weld root, heat affected zone and base metal.

4.4.1 Features of the welded samples

The micrographs of the weld matrix of these plates (figure 4.18) show the presence of some black globular particles. To identify these particles first of all the polished surface of the weld portion of these plates were scanned in SEM. The SE images of these plates (figure 4.19) again revealed the presence of some black globular particles in the weld matrix. These globules were more prominent in the corresponding BSE images of the plates (figure 4.20). The BSE images clearly showed the compositional difference between these particles and the remaining weld matrix.
Micrographs of plates 4, 5, and 6
Location: Weld Portion
Magnification: 400X

Figure 4.18 (a): Plate 4
Figure 4.18 (b): Plate 5
Figure 4.18 (c): Plate 6
Secondary and Backscattered Electron images of plates 4, 5 and 6
Location: Polished weld portion
Magnification: 1000X

Figure 4.19(a): SE image of plate 4
Figure 4.19(b): SE image of plate 5
Figure 4.19(c): SE image of plate 6
Figure 4.20(c): BSE image of plate 6
4.4.2 Identifying the secondary phases

EDX analysis of this particles and remaining weld matrix was performed. The particle analysis is shown in figure 4.21 (b) which indicates around 24 percent of magnesium. Whereas weld matrix analysis, shown in figure 4.21 (a), indicates the presence of only 3-4 percent of Mg that resembles with the filler alloy composition. On the other hand, the binary aluminum magnesium equilibrium diagram informs the formation of MgAl₃ precipitates at this condition. Thus combining the knowledge of Al-Mg binary diagram and the EDX results it can be said that the black particles in the micrographs are MgAl₃ precipitates.

Quantification results

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Figure 4.21 (a): plate 5 (Al-Mg filler) Weld matrix analysis

Quantification results

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Figure 4.21 (b): plate 5 (Al-Mg filler) Weld particle analysis
4.4.3 Characteristics of the Mg$_2$Al$_3$ precipitates

This Mg$_2$Al$_3$ precipitates have different orientation and distribution at different locations of the plates. From the micrographs (figure 4.22) it is found that Mg$_2$Al$_3$ precipitates are more concentrated in the weld root than that in the weld portion (figure 4.18). This is because of high heat dissipation rate of the root (explained in section 4.3.3).

**Micrographs of plates 4, 5 and 6**
Location: Weld Root Area
Magnification: 400X

![Figure 4.22(a): Plate 4](image)

![Figure 4.22(b): Plate 5](image)

![Figure 4.22(c): Plate 6](image)
The heat affected zone micrographs of these plates show a different type of structure from the weld portion and base metal. The weld zone and HAZ show the presence of some crack lines. Similar findings were observed by Lippold, J.C., Nippets, E.F., and Savage, W.F. (1977), where they made an investigation of hot cracking in 5083-O Aluminium alloy weldments. Moreover, Steenbergen, J.E., and Thornton, H.R. (1970) made a quantitative determination of the conditions for hot cracking during welding for aluminium alloys and this investigation also supports the formation of this type of cracking at the HAZ. This type of cracks did not form in case of 4043 filler metal. This is also supported by C. Huang and S. Kou (2004) who investigated liquation cracking in the partially melted zone of full penetration welds of alloy 6061. The welds of alloy 6061 was made with both filler metals 5356 and 4043. And from the investigation it was found that liquation cracking occurred with 5356 but not with 4043.

These cracks form during solidification when the lowest melting point constituents (Mg2Al3 precipitates) are pushed to the grain boundaries by the solidification fronts as the solid particles grow in size. The difference in melting point between the low melting point constituents and the bulk of the metal is sufficiently great. As a result, the liquid film along the grain boundaries apart as the metal cools and contracts creating solidification cracking (Gittos, N.F., and Scott, M.H.). The formation of solidification liquation cracking is affected by heat input. An increase in heat input causes a decrease in solidification cracking, because temperature difference between the low melting point constituents and the bulk of the metal decreases as the heat input increases. That's why plate 6 shows less solidification cracking. Similar observations were found by Dudás, J.H., and Collins, F.R. (1966).
Micrographs of plates 4, 5, and 6
Location: HAZ and base plate
Magnification: 200X
4.4.4 Relationship between microstructure and hardness

The change in microstructure with heat input is also supported by the microhardness profiles of these plates. Here also Knoop hardness test was performed at different locations of the plates. Comparison of hardness at different locations of plate 4, 5 and 6 are shown in figure 4.24(a,b,c). It can be seen the hardness value at different locations of plates 4, 5 and 6 does not behave as those of plates 1, 2 and 3. Because Al-Si eutectic mixture and MgAl2 globules do not have the same effect on the mechanical properties. Here hardness value remains almost same at different portions of the weld.

Figure 4.24(a): Hardness at different locations of plate 4
Figure 4.24(b): Hardness at different locations of plate 5

Figure 4.24(c): Hardness at different locations of plate 6
Now comparing the hardness value at the same weld portion of different plates of different current setting (figure 4.25(a,b,c)) it is found that there is not any major change in hardness value with increasing current content. The macrohardness values (figure 4.26) of these plates also show the same trend.
Comparing weld root portion among plates 4 (145A), 5 (175A) and 6 (195A) Mg filler, Base plate - pure aluminium

Figure 4.25(c): Comparison of weld root among plates 4, 5 and 6

Macrohardness values of plates 4, 5 and 6
Load-110 Kg, Duration - 15 seconds

Figure 4.26: Macrohardness values of plates 4, 5 and 6
4.4.5 Relationship between fractograph and mechanical properties

From figure 4.27 it is found that the impact energy at the HAZ is always higher than the impact energy at the weld portion. Because the impact properties of the HAZ are influenced by the impact property of the base plate that have a high impact energy. On the other hand, impact property at the weld portion tend to increase with an increase in heat input. It may be due to the decrease of
solidification cracking at the higher heat input. Again the UTS values of these plates (figure 4.28) remain almost unchanged with heat input. Fractured samples found from impact tests were scanned in the scanning electron microscope. The fractographs of these samples are shown in figure 4.29.

**Fractographs of plates 4, 5 and 6**
**Location: Weld Portion, HAZ and Base Plate**
**Magnification: 1000X**

![Fractographs of plates 4, 5 and 6](image_url)
The fractured surface of the HAZ of these plates (figure 4.29(b, d, f)) show dimple features. The micrographs of these plates at the HAZ showed the presence of liquefaction cracking. This preexistence of liquefaction cracking fastens the separation of metals during impact, resulting in decrease in impact energy than the pure aluminium plate. On the other hand the fractured surface of the weld portion of these plates (figure 4.29(a, c, e)) show faceted features that causes brittle fracture.
4.5 Plates 7, 8 and 9

Plates 7 and 8 were welded with current setting of 145 and 175A respectively, where 4043 filler was used in each case. The base plate was an alloy of Aluminium and Magnesium of 5xxx series. Micrographs of plates 7 and 8 taken at different locations of the samples are shown below.

4.5.1. Features of the welded samples

Micrographs of plates 7 and 8
Location: weld portion
Magnification: 400X

These micrographs of plates 7 and 8 (figure 4.30(a,b)) show the secondary phase which were previously identified (in case of plates 1, 2 and 3) as eutectic mixture of aluminium and silicon. To ensure the formation of this eutectic mixture here also SE and BSE images of these plates were taken (figure 4.31 and 4.32). The EDX analysis of these secondary phases was also performed (figure 4.33) which ensured the formation of Al-Si eutectic mixture. The EDX analysis indicates the formation of another phase of Mg-Si. The presence of this phase affects the fracture property of these plates.
Secondary and Backscattered Electron Images of Plates 7 and 8
Location: Polished weld portion
Magnification: 800X

Figure 4.31(a): SE image of plate 7
Figure 4.31(b): BSE image of plate 7

Segregation

Figure 4.32(a): SE image of plate 8
Figure 4.32(b): BSE image of plate 8
ENERGY DISPERSIVE X-RAY ANALYSIS OF PLATES 7 AND 8

Quantification results

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Figure 4.33(a): Plate 7 (Al-5% Si filler) Weld matrix analysis

Quantification results

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Figure 4.33(b): Plate 7 (Al-5% Si filler) Weld particle analysis
4.5.2 Characteristic of the eutectic mixture

Like plates 1, 2 and 3, here also the eutectic mixture is different in distribution, shape and size not only at different location of the same plate but also at the same position of different plates. In the weld root (figure 4.34) the eutectic mixture is very much closer than that in the weld portion (figure 4.30) (Zhang, J., Fan, Z., Wang, Y.G., and Zhou, B.L.). Comparing welded portion of plate 7 (figure 4.30(a)) and plate 8 (figure 4.30(b)) it can be said that the eutectic mixture increases in size with increasing current content. The reason explained in section 4.3.3. In this case where Al-Si filler was used in Al-Mg base plates some segregation appears in the weld portion (figure 4.31(b)) which may be due to the formation of Mg2Si phase.

Quantification results

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Figure 4.33(c): Plate 7 (Al-5% Si filler)
Analysis of segregation
Micrographs of plates 7 and 8  
Location: weld root area  
Magnification: 400X

Figure 4.34(a): Plate 7  
Figure 4.34(b): Plate 8

Figure 4.35: Base plate  
5xxx series
From the heat affected zone micrographs of these plates it is clear that in all cases there is some diffusion or dilution of this eutectic mixture. Occurrence of dilution is clear if we compare the micrographs of HAZ (figure 4.36) and base plate (figure 4.35). This dilution affects the fractograph of HAZ.

Micrographs of plates 7 and 8
Location: HAZ
Magnification: 200X

Figure 4.36 (a): Plate 7
Figure 4.36 (b): Plate 8

4.5.3 Relationship between microstructure and hardness

The change in microstructure with heat input is also supported by the microhardness profiles of these plates. Knoop hardness test was performed at different locations of these plates. Comparison of hardness at different locations of plate 7 and 8 are shown in figure 4.37(a) and figure 4.37(b) respectively. These microhardness profiles show that plate 7 has high hardness values at the root portion than the remaining weld portion but plate 8 shows almost same hardness values at the weld portion and the root portion. This is because in plate 7 heat input was low, so root portion solidified rapidly than the remaining weld portion resulting in high hardness value. On the other hand in plate
8, heat input was high due to high current, so the root did not solidified as rapidly as plate 7, resulting in same hardness value as that of the weld portion. So it can be said that the increasing current content resulted in structural homogeneity.

Figure 4.37(a): Comparison of hardness at different locations of plate 7

Figure 4.37(b): Comparison of hardness at different locations of plate 8
Now comparing hardness at the same weld portion of plates 7 and 8 it was found that plate 8 showed higher hardness value at weld top and weld middle portion than plate 7 (figure 4.38(a) and 4.38(b)). But at the root portion both plates showed almost equal hardness (figure 4.38(c)). This is because of the eutectic mixture that is larger and coarser in plate 8 than plate 7 at the weld portion but almost the same at the weld root area. The macrohardness value of these plates (figure 4.39) show the same trend that is plate 8 has higher hardness value at the weld portion than plate 7.

![Figure 4.38(a)](image1)

**Figure 4.38(a):** Comparison of weld top hardness of plates 7 and 8

![Figure 4.38(b)](image2)

**Figure 4.38(b):** Comparison of weld middle hardness of plates 7 and 8
Figure 4.38(c): Comparison of weld root hardness of plates 7 and 8

Figure 4.39: Macrophase hardness values of plates 7 and 8
4.5.4 Relationship between fractographs and mechanical properties (plates 7 and 8)

The impact energy of these plates (figure 4.40) show that HAZ have almost the same impact energy as the weld zone. But in the previous cases HAZ always showed higher impact energy than weld zone. Maybe the segregation of Mg, Si is responsible for this. Similar findings were observed by C.Huang and S.Kou where the presence of solute segregation resulting in a poor mechanical performance. Again N.P.Gittos and M.H.Scott (1981) made an investigation on heat affected zone cracking of Al-Mg-Si alloys. From the investigation Al-Mg alloys were found to be preferable to Al-Mg-Si alloys for welded fabrications and maximum resistance to HAZ cracking was obtained using Al-Si filler. Besides this J.H.Dudas and F.R.Collins(1966) made another investigation on preventing weld cracks in high strength aluminium alloy. From the investigation it was found that Al-Mg-Si alloys are highly crack sensitive because they contain approximately 1.0% Mg,Si, which is near the peak of the hot cracking curve. Cracking is lowered by dilution of the weld with excess magnesium (Al-Mg filler metals) or excess silicon (Al-Si filler metals).

Figure 4.40: Impact Energy of plates 7 and 8
The fractographs of the weld portion (figure 4.41) show a cast dendritic structure which may be due to the presence of Mg. Because this type of fractograph was not found in case of plates 1, 2 and 3 where also 4043 filler was used. The fractographs of HAZ (figure 4.42 (a,b)) show a mixture of cast structure (as fractograph of weld portion) and dimples. The presence of cast structure (characteristics of weld portion) at HAZ is due to dilution at this zone. The fractograph of base plate (figure 4.43) exhibits fewer and larger dimples because of the presence of relatively few microvoid initiation sites.

Fractographs of plates 7 and 8
Location: weld portion, HAZ and base plate
(Magnification: 1000X)

Figure 4.41(a): Plate 7 (notch at weld portion)
Figure 4.41(b): Plate 8 (notch at weld portion)
Figure 4.42 (a): Plate 7 (notch at HAZ)

Figure 4.42 (b): Plate 8 (notch at HAZ)

Figure 4.43: Base plate
5xxx series, Al-Mg alloy
Finally another base plate of 5XXX series was welded at 175 A with the 5356 (Al-Mg) filler metal. The micrographs of this plate taken at the weld portion (figure 4.44(a)), weld root (figure 4.44(b)) and HAZ (figure 4.44(c)) are shown below.

Micrographs of plate 9
Location: Weld Portion, Weld Root Area, HAZ
Magnification: 400X

Figure 4.44(a): weld portion
Figure 4.44(b): weld root area
Figure 4.44(c): HAZ
The weld portion show some black globular particles like plates 4, 5 and 6. Similarly as all the previous welded sample here also the SE and BSE images (figure 4.45) of this plate were taken to identify the black globular particles of the micrograph and again it was identified from the EDX analysis (figure 4.46(a, b)) as Mg,Al, precipitates. The size and shape of these precipitates were different in at different location of the weld (Explained in section 4.5.3). Besides the presence of Mg,Al, precipitates, here again solidification cracks found. Similar findings were observed by Dowd, J.W. (1952).

SE and BSE images of plate 9
Location: Polished weld portion
Magnification: 800X

Figure 4.45(a): SE image of plate 9
Figure 4.45(b): BSE image of plate 9
EDX analysis of plate 9

Quantification results

<table>
<thead>
<tr>
<th>Element</th>
<th>Wt%</th>
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<tbody>
<tr>
<td>Al</td>
<td>rest</td>
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<tr>
<td>Mg</td>
<td>5%</td>
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</table>

Figure 4.46(a): plate 9 (Al-5% Mg filler)
Weld matrix analysis

Quantification results

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<tbody>
<tr>
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<td>Mg</td>
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Figure 4.46(b): Plates 9 (Al-5% Mg filler)
Weld particle analysis
The comparison of hardness values at different locations of plate 9 is shown in figure 4.47 and the impact energies are shown in figure 4.48.

![Comparison of hardness values at different locations of plate 9](image1)

**Figure 4.47: Comparison of hardness values at different locations of plate 9**

![Impact energy of plate 9](image2)

**Figure 4.48: Impact Energy of plate 9**
The fractured surface of the impact test specimens were scanned in the scanning electron microscope. These fractographs of are shown below.

Fractographs of plate 9
Location: Weld Portion and HAZ
Magnification: 1000X

Figure 4.49 (a): notch at weld portion
Figure 4.49(b): notch at HAZ

Fractured surface of weld portion of plate 9 (figure 4.49(a)) show dimple features. On the other hand the fractograph of heat affected zone of this plate (figure 4.49(b)) show a mixed mode of fracture between base plate and weld portion. Dilution in the HAZ acts as precursor of cracking that result in a decrease in impact energy. But here HAZ show a low impact energy than the weld portion, whereas in the previous cases HAZ always showed higher energy than the weld portion. As in this case only one current setting was used for welding, so it needs further study to explain this phenomenon.
SUMMARY AND CONCLUSIONS

In the present research work two different grades of aluminium plates (1xxx and 5xxx series) were welded with two different filler metals (4043 and 5356) and with different current settings. Tungsten Inert Gas (TIG) welding process was used for welding. After welding nondestructive testing was performed to determine weld soundness. Then optical and SEM micrographs were taken at different locations of the weld. And various mechanical tests such as microhardness test, macrohardness test, impact test, tensile tests were performed to observe the effect of heat input on the structure and property of the weld. It can be said that a systematic investigation was made on TIG welding of aluminium alloy to determine the probable reasons for evolution of weld porosity and the solidification cracking of aluminium weld and to improve the structure-property relationship of weldment by controlling heat input.

From the results it can be concluded that:

- When 4043 filler (Al-Si filler) was used for welding pure aluminium plates, Al-Si eutectic mixture formed in the weld portion. The eutectic mixture was different in size, shape and orientation at different current settings and at different locations of the welded samples. At the highest current setting that is at the highest heat input the eutectic mixture was coarsest and largest in size and formed a continuous network. The hardness value was the highest at the coarsest and largest eutectic mixtures that is at the highest current setting. It was also observed that difference in hardness values between different portions of the weld decreases as the welding current increases because high heat input created more dilution in the weld structure. Moreover this combination of welding did not create any problem of solidification cracking. The impact energy and tensile strength improved with increase in current content.

- When 5356 filler metal (Al-5%Mg) was used for welding pure aluminium plates globules of Mg₂Al₃ precipitates were formed. Here also the precipitates were different in size, shape and orientation at different current settings and at different locations of the welded
samples. In this case solidification cracking appeared at the weld portion and at the HAZ. Here the tendency for these defects decreased in the case when there was sufficient time for solidification after welding and when the temperature difference between the precipitates and the bulk material decreased. As a result when welding conducted at the highest current setting the tendency for solidification cracking decreased. The impact energy improved with an increase in heat input may be due to this reason. Here the hardness value and the tensile strength remained almost the same for all current setting.

When 4043 filler metal was used for welding a base plate of 5xxx series (Al-Mg alloy) again Al-Si eutectic mixture formed but another phase of Mg, Si also formed during welding. The characteristics of the eutectic mixture was the same as the previous welding that is at the highest current setting the eutectic mixture was the largest, coarsest and continuous in nature. However another phase of Mg, Si was also found and suspected to be responsible for decreasing the impact energy. In this case the microhardness profiles exhibit that increase in current content results in structural homogeneity. Here also the impact energy improved at the highest current setting. When 5356 filler metal was used for welding a base plate of 5xxx series then only one current setting was used for welding, so it needs further study to explain the characteristics of this welded sample.
Suggestions for further studies

The effect of weld parameters on the properties of aluminium weldment produced by TIG welding was studied in the present research work. Two different grades of aluminium plates of 1xxx series and 5xxx series were welded with two different types of filler metals and with different current setting. Here various mechanical tests such as impact, tensile, hardness tests were performed to establish a relationship between structure and property of the weldments. From the research work the followings can be suggested for further studies:

1. Corrosion study of the weldments can be performed to observe the effect of heat input on the corrosion properties of the weldments.

2. Fracture toughness test of the weldments can be performed to have better understanding of the mechanical properties of weldments.

3. The extent and effect of tungsten inclusion into the weldment can be measured.

4. Better welding techniques to reduce the solidification cracking can be studied.
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