SOME PRACTICAL ASPECTS OF WELDING HEAT TREATABLE ALUMINIUM ALLOYS

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INTRODUCTION

Aluminium alloys are extensively used for a wide range of applications due to several attractive properties inherent in this group of materials. Excellent corrosion resistance, good toughness even at low temperatures and high strength to weight ratio of several grades of Aluminium alloys have led to increased industrial applications for these alloys in key areas like aerospace and defense, cryogenic, marine, transportation, tankage and piping. A great many of these applications involve welding as a means of application. While many alloys of aluminium including the high strength heat treatable alloys are weldable in principle and infact welded regularly, yet problems do arise occasionally.

For successful welding of aluminium alloys, it is essential that the characteristics of the alloy, particularly those pertaining to welding are properly understood and followed. Aluminium has a high affinity for oxygen and forms a tenacious high melting oxide layer on its surface rapidly at elevated temperature. This oxide layer has much higher melting temperature than aluminium itself and does not dissolve in the liquid metal. This oxide layer needs to be removed in process for a successful welding of aluminium. Besides, aluminium possesses a higher thermal conductivity together with a higher coefficient of thermal expansion than steel. The heat treatable aluminium alloys when welded in the heat treated condition suffers a softening in the HAZ areas, which needs to be understood and should be given allowance for, in design calculations. However, the most serious problem that is encountered in the welding of aluminium alloys, particularly for the heat treatable aluminium alloys is cracking sensitivity of these alloys. It has been the endeavour of the authors to highlight the areas of problems, processes and techniques based on WRI's own experience to produce satisfactory welds in aluminium alloys.

ALUMINIUM ALLOYS

Aluminium alloys are primarily classified based on the principal alloying element present as shown in Table 1. Many of these alloys respond to a precipitation hardening heat treatment for strengthening and these are in general termed as heat treatable aluminium alloys. Important heat treatable alloys are listed in Table 1.

1. Welding of heat-treatable alloys

a) Joint Efficiency

The heat treatable aluminium alloys when welded in the heat treated condition suffer a softening in the HAZ due to re-solutioning and over ageing of the age hardening precipitates. As a result, the strength and hardness in the as welded conditions become lower than the fully heat treated base metal. The joint efficiency in the as welded conditions remains usually in the range of 60 to 70%. This loss in strength and hardness is irreversible unless a full T_6 heat treatment comprising solutionizing and ageing is carried out which is seldom practiced. The only exception is the Al-Zn-Mg alloy system which undergoes automatic reversion and the whole of the HAZ regains properties in course of time by natural ageing. However, for all other heat treatable alloys the application of minimum heat input and a faster cooling are required to minimize the loss

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in strength and hardness and thereby to achieve a better joint efficiency.

b) Cracking Sensitivity

The cracks appearing in the aluminium alloy weldments are basically hot cracks. These cracks occur either in the fusion zone in the form of solidification crack or hot tearing, and in the HAZ of the base metal as liquation crack [1]. There is no single factor, which can be solely held responsible for hot cracks in aluminium alloy welds. It is a complex process based on the interaction of mechanical restraints, thermal strains and metallurgical factors which encompass the chemical composition of the base metal, the weld metal, segregation of the solute elements as well as the grain size and shape and even orientation of the grains [2.3.4].

Restraint is the mechanical factor and is the result of restrictions imposed on the heated areas (weld and HAZ) to undergo thermal expansion and contraction during the welding thermal cycle. The restriction is primarily caused by the rigid fixturing aimed to control distortion. The coefficient of thermal expansion of aluminium is roughly twice that of steel. The failure to take this data in consideration while designing the fixtures largely accounts for the restraints related cracking problems in aluminium welds. It is therefore possible to avoid or greatly reduce the risk of restraint induced cracking by properly designing the fixtures for aluminium alloy welding.

Thermal Strains are caused during the thermal cycles experienced by the joints during welding. As mentioned above the co-efficient of thermal expansion of aluminium alloys is roughly twice that of iron based alloys and therefore, for the same change in temperature the shrinkage strains in aluminium weldments are roughly twice of those in steel weldments. This makes the aluminium alloys more susceptible to cracking as compared to steel. However, it is to be kept in mind that the thermal stresses/strains alone are not capable of producing cracks. It is the interaction of the mechanical restraints, thermal strains and the metallurgical factors that finally leads to a sound or cracked weld. However, since the thermal strains are inevitable in a fusion weld, it would be prudent to keep the situation under control by proper selection of heat input. High heat inputs such as high currents and slow welding speeds are likely to aggravate the situation [5, 6].

It is evident by now that the metallurgical factors contribute quite significantly in the generation of the cracks. Most aluminium alloys, particularly the heat treatable alloys have wide freezing ranges and are thus inherently sensitive to hot cracking [3]. Looking at the compositional aspects it is clear that most commercial alloys are not strictly binary systems. Minor alloy additions are made to the basic binary alloy systems to increase the strength. Several high strength precipitation hardenable aluminium alloys rely on complex alloying addition to develop properties; however, these additions dramatically increase weld

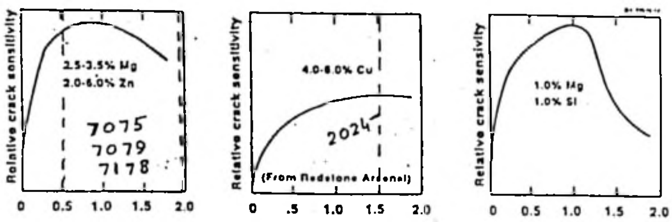


Fig. 1. Weld crack sensitivity of two common quaternary aluminum alloy systems (Al-Mg-Zn-Cu and Al-Mg-Si-Cu) and a common ternary system (Al-Cu-Mg).

crack sensitivity [1]. The most notable examples are alloys AA2024 (Al-4.4 Cu-1.5 Mg) and AA7075 (Al-5.6 Zn-2.5 Mg-1.6 Cu). In the case of alloy AA2024, the addition of 1.5% Mg has drastically increased the crack sensitivity of the Al-Cu alloy, whereas the addition of 1.6% Cu has rendered the alloy AA7075 (Al-Zn) unweldable due to enhanced crack sensitivities. (Fig. 1).

2. Role of Filler Metals

The filler metal plays a very important role in avoiding weld cracking. In fact, the primary method for eliminating cracking in aluminium alloy welds is to control weld metal composition through filler additions [1]. A filler metal with a melting temperature below that of the base metal greatly reduces the tendency for intergranular cracking in the HAZ. A filler metal with this characteristics minimizes the stresses imposed by the solidification shrinkage of thc weld metal until any low melting phases in the HAZ have solidified and developed sufficient strength to resist the stresses [1, 7]. A comparative crack sensitivity chart of some aluminium alloys/filler alloys combinations is given in Fig. 2. Weld metal cracking can be prevented by welding with a filler metal of higher alloy content than the base metal [7]. For example, 6061 alloy with a nominal Si content of 0.6% is extremely crack sensitive when welded with 6061 filler metal or fused without filler metal addition (Fig. 3).

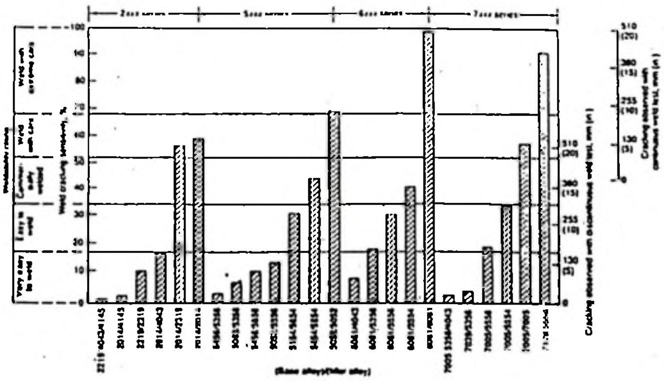


Fig. 2. Relative Crack sensitivity ratings of selected aluminum (base alloy/filler alloy) combinations.

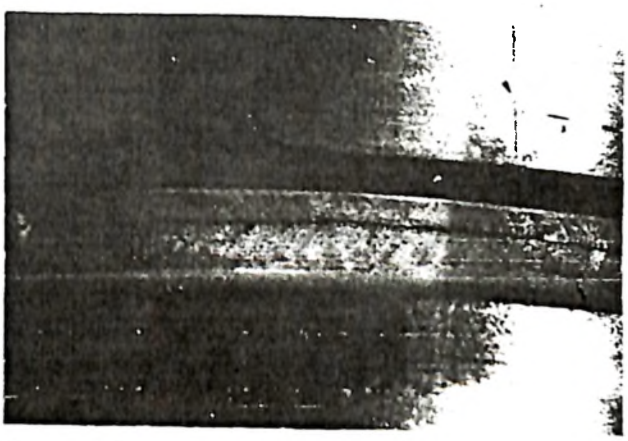


Fig. 3. Cracking of 6061 weld when made without filler metal addition.

WELDING PROCESSES

While several welding processes like gas welding, SMAW, TIG, MIG, Plasma arc, Electron Beam and Laser Beam Welding processes are used to weld aluminium for various types of applications, the discussion in this paper will be restricted to the two most widely used arc welding processes, namely TIG and MIG.

1. TIG Welding

To weld aluminium and its alloys by TIG process, the alternating current is used as the welding current (AC TIG) while DC TIG is used to weld most of the other ferrous and non ferrous metals (except Al and Cu). In the AC TIG welding the electrode positive half cycle provides oxide cleaning from the weld pool and the penetration is obtained in the electrode negative half cycle. So penetration obtained in this process is only average. But it is the most successful and widely

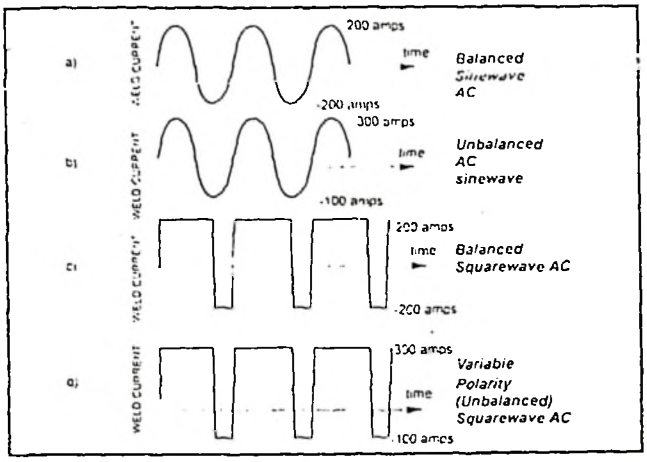


Fig. 4. Examples of AC welding currents.

used method of Manual TIG welding of aluminium. Types of commonly used alternating welding current include balanced sinusoidal wave, unbalanced sine wave, balanced square wave and variable polarity square wave which are shown in Fig. 4 [8].

Sine Wave

The frequency of the current reversal is typically fixed at the standard 60/50 Hz frequency of the primary power. As shown in Fig. 4, the sinusoidal wave form exhibits significant periods of time near zero current where the voltage is too low to maintain or reignite the arc. Some means of stabilizing the arc and reigniting the arc during current reversal is required with conventional sinusoidal welding power sources. The most common method used to accomplish this is with the continuous use of a high frequency arc starter.

Square Wave

Square wave AC welding power sources can change the direction of the welding current in a short period of time. This rapid change in current prevents arc extinction as the current changes polarity. When this rapid current reversal is combined with the high electrode and base metal temperature at current reversal, the square wave AC allows the arc to be reignited without the aid of arc reignition equipment. Another important advantage of square wave AC is that the time duration of the electrode positive and electrode negative portions of the wave are adjustable. In most cases the electrode negative part is maintained for longer time as a shorter duration for the electrode positive part is adequate to clean the oxide layer in most cases. By this the penetrating efficiency of the arc is increased.

Variable Polarity

The term variable polarity describes an alternating welding current that is asymmetrical about the zero current level, *i.e.*, the magnitudes of the current in the electrode positive and electrode negative parts of a wave are not equal. This type of power source was originally made for the welding of aluminium alloys by the plasma keyhole technique [9]. However, variable polarity power supplies are well suited to the TIG process and have made significant impacts on the mechanized pipe and tube welding industry [8]. X-ray quality welds routinely produce in all types of aluminum including those prone to porosity.

2. MIG Welding

MIG welding is also widely used to weld aluminium and its alloys. Its high deposition rate and suitability to positional welding make it an attractive process. However, for critical applications where high quality welds are required; MIG welding process is often overlooked since it is feared by many fabricators that it would not be possible to maintain the high quality requirements with this process. Though there are some typical problems associated with this process but they are not insurmountable [10]. Porosity formation considered as a major problem in MIG welding. Lack of penetration, lack of fusion and burn through in root pass welding are the other common defects encountered with conventional MIG welding of aluminium. Hence, it is vitally important that adequate attention is paid to suitable welding conditions [11].

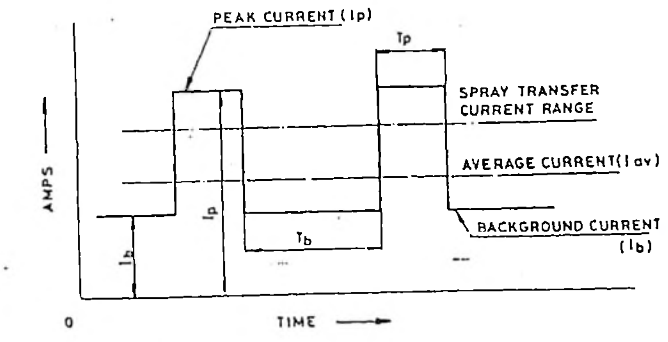
It is well known that the spray mode of metal transfer is most suitable for welding aluminium. To achieve spray mode in conventional MIG welding, current and voltage settings must be kept fairly high. For example, current in the range of 180-200 A and voltage in the range of 22-24V are required to achieve spray mode of metal transfer with 1.6 mm dia wire. To match these settings, wire feed rate has to be maintained in the range of 5.8 - 6 m/min. The MIG welding carried out with the above parameters causes certain difficulties as enumerated below.

Conventional MIG welding in the spray mode will produce large weld pool at lower welding speeds (<400 mm/min) leading to weld pool flooding or weld metal running ahead of arc which can cause lack of penetration defects in the root run. Hence, arc travel speeds shall be kept sufficiently high to avoid these problems. However, at higher speeds the probability of lack of fusion and lack of penetration increases particularly in thick welds. Conversely, if arc is pushed at little lower speeds it would cause excess penetration and burn through defect. Thus to achieve joints with controlled penetration is practically impossible with conventional MIG welding without backing.

Synergic MIG

The introduction of synergic MIG process has revolutionised the welding of aluminium with its special characteristics. It provides controlled metal transfer and easier manipulation of the weld pool by providing spray transfer at very low average currents compared with those of conventional MIG welding. Thus, it has greatly extended the previously limited scope of the conventional MIG process. The developed countries were quick to adopt this process but the potential is yet to be exploited in our country.

Synergic MIG welding is a transistorised controlled pulsed MIG welding process wherein controlled metal transfer is achieved in such a way that for each pulse one drop is detached having a diameter more or less equal to wire diameter. Current is pulsed between low level (back ground current) and high level (peak current) for suitable duration so that average current is kept in the short circuiting range but metal transfer is achieved in spray mode. The high peak current pulse is kept well above the transition zone where only spray transfer is achieved. The low level background current is maintained which is sufficient to maintain the arc but it is below the transition current (Fig. 5). Thus at very



$I_{av} \times T = I_p T_p + I_b T_b$, $T = T_p + T_b$, $F = 1/T$

Fig. 5. Output wave form of current in synergic MIG welding.

low average current spray transfer mode can be operated which is impossible to achieve in conventional MIG welding, *e.g.*, for 1.6 mm diameter wire, spray mode of metal transfer can be achieved at an average current of 90 Amps. (Ip = 260A, Tp = 3ms, Ib = 50A and Tb = 15ms) with a wire feed rate just 2.3 m/min. It is possible to achieve spray mode even at an average current of 60 Amps.

It can be easily understood that weld pool flooding and associated problems as observed in conventional MIG welding can be overcome to a great extent by using this process. Fig. 6 shows the bead on plate trials on 6 mm plate with less ripples similar to TIG welding. Thin material can be welded with relatively large diameter electrodes and butt welds can be welded

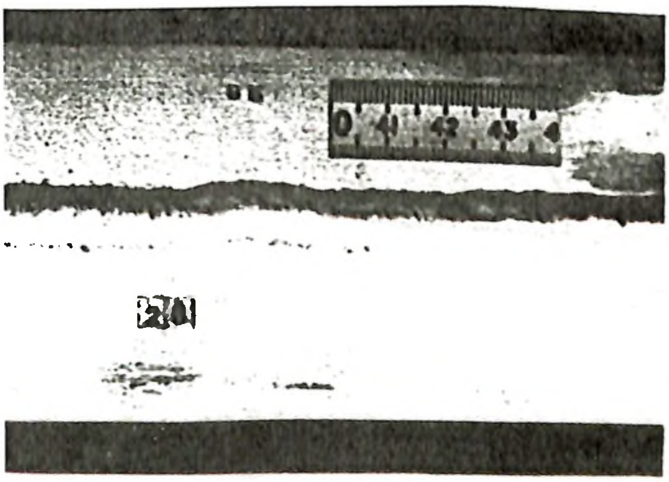


Fig. 6. Bead on Plate Synergic MIG Lp-350A; Ib-50 A; Tp-10ms Ave-136A; WS-350 mm/min; WF-43 m/min; T-6 mm.

without backing bars with controlled penertration with less skill requirements and with low heat input (Fig. 7). Root run welding backing can be performed with much greater ease as compared to conventional MIG welding (Fig. 8). Moreover, positional welding can be performed with relative cease with desirable penetration, bead

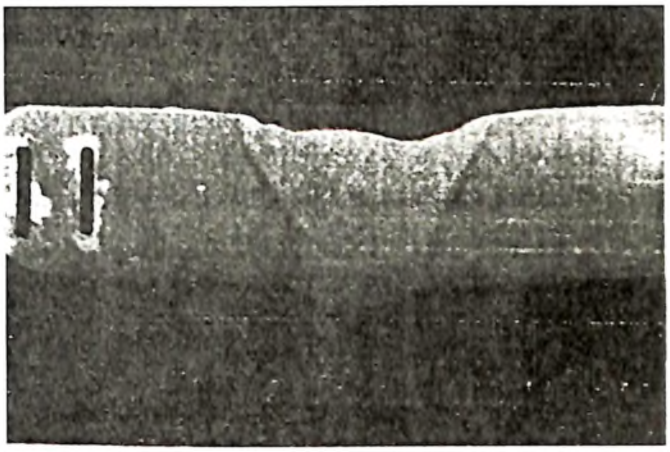


Fig. 7. Macrosection of root bead without backing - Synergic

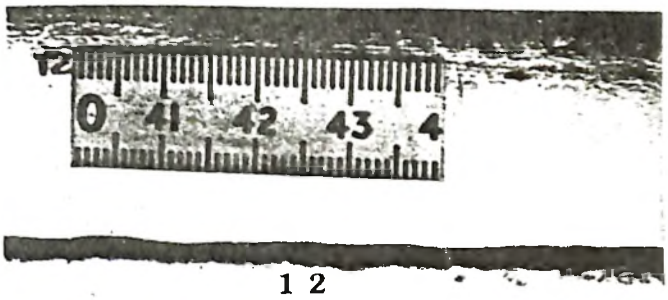


Fig. 8. Root Bead formation with backing - Synergic MIG.

shape and with negligible spatter at much slower welding speeds.

The direction of travel, gun angle and manipulative techniques arc basically the same as with conventional MIG welding. However, welder using pulsed MIG will be able to appreciate the distinct changes in operating characteristics of the weld pool as compared to conventional MIG welding. Good fit-up is essential. With suitable welding condition and travel speeds high integrity welds can be provided. Further, it allows the use of large diameter electrodes for wide range of thicknesses with combined advantage of improved quality and freedom from wire feeding problem often experienced with small diameter wires. Further, the risk of porosity is also significantly reduced since it provides stirring action in the weld pool [12, 13].

TECHNIQUES

In practical shop floor welding certain techniques are employed in conjunction with the basic welding processes to achieve a satisfactory welded joints. For welding of aluminium alloys the following techniques have been found useful.

1. Pre-Weld Cleaning

It is the most important activity that must be done before striking an arc to weld aluminium. Apart from general cleaning of dirt, oily matter, paint, etc., the weld groove and adjoining base metal area must be cleaned to remove layers of aluminium oxide. The removal of existing surface oxide layer must be done to obtain satisfactory weld joint in aluminium. The removal may be done by mechanical means like wire brushing, filing or by chemical cleaning in a suitable bath. Always use stainless steel wire brush for aluminium.

2. Inter-layer Cleaning

In multipass welding, the interpass cleaning of oxide layer helps reduce porosity formation as well as lack of fusion defects. Particularly, the corners and crevices as shown in Fig. 9 should be cleaned by wire brushing either manually are with wheel brush fitted to pneumatic grinders. The uneven beads having humps, etc., should be chipped off.

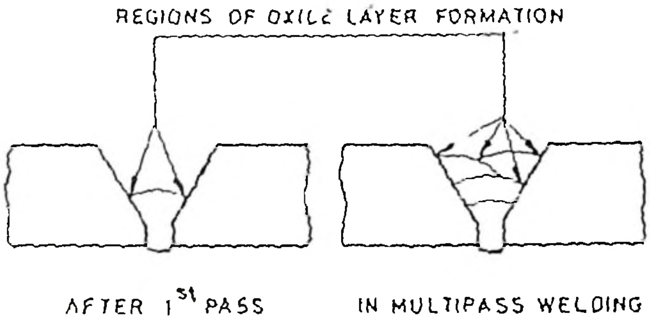


Fig. 9. Regions of oxide layer and porosity formation in multipass welding.

3. Use of backing Bar

Though it is not absolutely essential to use a backing bar in AC TIG welding of aluminium alloys, the use of it definitely produces better root bead formation and enhanced HAZ properties due to faster cooling rate produced by the chilling effect of the backing bars. The same is true for pulsed MIG also. However, as already discussed, the provision of a backing bar can be considering as an essential requirement for good root pass welding by conventional MIG welding.

4. Welding Progression

Forehand technique is always used to weld aluminium by TIG or MIG processes. For vertical welding it is always vertical up progression that is followed. For a pipe welding in 5G position the progression is always from 6 O'clock to 12 O' clock.

5. Controlled Agitation of weld pool

Turbulent convective fluid flow during solidification has been shown to produce a substantial reduction in porosity and grain size in aluminium welds deposited by the Gas Tungsten Arc Welding process. It has been found that electromagnetic stirring produced substantial reductions in the porosity in aluminium welds. Convection appears to be vital in accelerating the nucleation, growth and ultimate escape of bubbles from the molten pool [14].

This phenomenon was confirmed as welds produced by synergic MIG welding showed much less porosity compared to welds made by conventional MIG welding since pulsation between low and high level of current produced convective fluid flow and stirring action provided by the stiff arc of pulsed MIG welding which reduced formation of both primary and secondary porosity.

It was found in conventional MIG welding that pronounced rotary motion to agitate the weld pool by

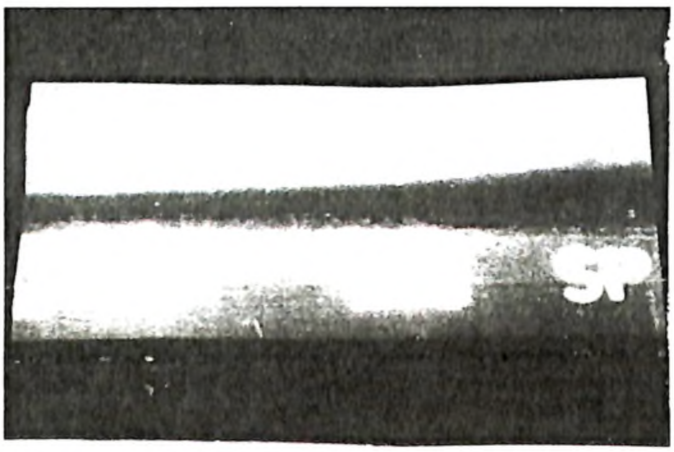


Fig. 10. X-Ray Photograph 14 mm thick butt weld with rotary motion of arc (Conventional MIG) Free from pores.

the manipulation of gun greatly reduced the formation of pores. This was found one of the most effective methods of controlling the porosity in MIG welding and technique has to be adopted to liberate the gas before the surface of the pool freezes [15]. With manual welding technique, this is achieved by maintaining a large but controllable weld pool and agitating it sufficiently to eliminate the gas bubbles. Fig. 10 shows X-ray photograph of 14 mm thick butt weld joint made employing this technique.

6. Argon-helium gas mixture

Though argon gas is widely used for TIG and MIG welding of aluminium, for thick welds Argon and Helium gas mixture in different ratios varying from 75:25, 50:50 and 25:75 can be used. Helium provides more heat in the arc and thus increases the depth of penetration. The hotter molten pool leads to slow cooling and less porosity formation.

CONCLUSION

1. For a successful welding of heat - treatable aluminium alloys, it is essential to understand the characteristics of the alloy.
2. Heat treated aluminium alloys suffer a loss in mechanical properties on welding and have lower joint efficiency in the as welded condition.
3. Heat treatable aluminium alloys are more sensitive to cracking which occur due to the interactions of mechanical restraint, thermal strains, and metallurgical factors like composition and microstructure.
4. Minimum heat input must be used to get higher joint efficiency with reduced risk of cracking.
5. A proper selection of filler metal helps minimise risk of cracking.
6. AC TIG is the most widely used method for low thickness as well as for critical jobs.
7. Spray mode of metal transfer is suitable for MIG welding of aluminium alloys.
8. Synergic Pulsed MIG provides spray type of metal transfer at lower average current. It provides better weld pool control and better quality of weld.
9. Welding techniques suitable for aluminium alloys should be followed to derive maximum advantage of the welding process chosen.

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Table 1: Alloy designations of wrought aluminium alloys.

Alloy system	Aluminum Series
Work-hardenable alloys	
Pure Al	1xxx
Al-Mn	3xxx
Al-Si	4xxx
Al-Mg	5xxx
Al-Fe	8xxx
Al-Fe-Ni	8xxx
Precipitation-hardenable alloys	
Al-Cu	2xxx
Al-Cu-Mg	2xxx
Al-Cu-Li	2xxx
Al-Mg-Si	6xxx
Al-Zn	7xxx
Al-Zn-Mg	7xxx
Al-Zn-Mg-Cu	7xxx
Al-Li-Cu-Mg	8xxx

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