PROBLEMS IN WELDING OF HIGH STRENGTH ALUMINIUM ALLOYS

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INTRODUCTION

ALUMINIUM and its alloys find a wide application in today's world specially in Aerospace, Defence, Nuclear and critical components where strength to weight ratios are critical and overall weight should be as less as possible. Generally Aluminium and its alloys are difficult to weld and require special techniques, machines, high purity gases and highly skilled specially trained welders.

GTAW & GMAW are commonly used welding processes. Each alloy is different from other and needs correct selection of filler wire for welding (Annexure-I). Some of the alloys are heat treatable and after heat treatment they acquire strength very close to steel (Annexure - 2, 3 & 4). .

Major problems in welding of aluminium are porosity, cracks, lower as welded strength, lower ductility, stringent heat treatment, requirements. With recent development in welding machines, wide choice of filler wires and improved techniques for welding edge preparation and cleaning of same can reduce problems but cannot be totally eliminated.

Alloy 6061 Condition	UTS Kg/cm2	Yield Kg/cm2	El	Remarks
O-Weld-T6	28	22	1.2%	in PM
T6-weld	17	12	6.8%	in PM
Parent Metal in T6	29	23	15%	-

This paper describes some of the causes and the solutions based on parctical experience.

Weldability

This is a general term used to indicate whether an alloy under consideration can be selected for the intended use after welding. End use can be only decorative sealing of the two articles, or it may be for leak tightness or it may be for getting the full strength either in tensile or in compression or it may be for good corrosion resistance. For example a aluminium structure like bridge or a tower will require weldability of that alloy for the full strength whereas a tank for storage of process fluid will require strength, leak tightness and corrosion resistance.

There are some alloys which impart good strength in as welded condition with fair amount of ductility but the same alloy gives extremely good strength at the cost of poor ductility after heat treatment. e.g. A6061 has good weldability using ER 4043, or ER 5356 type of filler wire in both annealed ('O' condition) and in quenched and tempered condition (T6). Typical values which are easily achievable are given in Table-I.

This shows sequence of welding and heat treatment is crucial and depending upon application sequence is to be decided. Another important aspect of Aluminium is that, the failure is always in Heat affected zone (HAZ). Most of the high strength alloys as welded using filler wires of different chemistry than the alloy itself. There are few wires which are of matching composition and are used only when alloy is selected for better corrosion resistance.

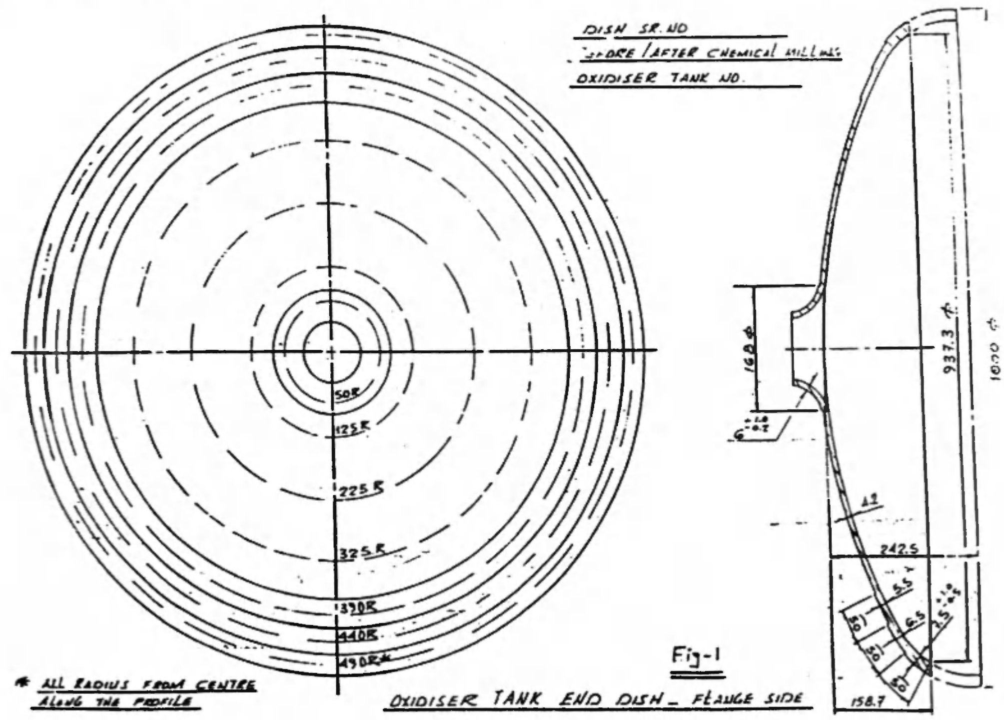


Fig 1 : Oxidiser tank end dish - FLANGE SIDE

Most important consideration in Aluminium as far as strength is concerned is lower as welded strength in HAZ, In other words Annealing of HAZ is a big concern in high strength Aluminium alloys. Base metal other than this small HAZ and weld metal is of higher strength but HAZ is weak, hence sequence of heat treatment, forming, welding and other related processes are important. In steel and other non ferrous alloys, this phenomenon is no significant. For this reason some of the Aluminium tanks are fabricated with chemical etching/milling or electro-chemical milling of pockets in higher strength material. Fig-1 shows a typical chemical milled dish end for one of such Tanks. Thickness at the weld joint is kept maximum to take care of lower strength in HAZ as shown in Table-1

Chemical or electrochemical milling of Aluminium alloys is simple and by this total weight of the tank can be reduced almost by 50%. Areas nearby welding only need to be of higher thickness. There is no saving in material cost as starting thickness is same as what is required in HAZ. Also there is a additional cost of milling. Hence this process of fabrication of tanks is limited to critical applications in Aerospace where strength to weight ratio should be as high as possible and overall weight is to be kept minimum.

Another aspect is heat treatment of aluminium. This is done in two stages, first plates in annealed condition are brought to T4 condition by solution quenching and later on it is further strengthened by artificial ageing to reach T6 condition. Welding can be carried out in any of the above conditions. Heat treatment of completed tanks requires huge furnace with special spray nozzle for solution quenching. Hence individual components like Dish ends, Shell, Nozzles, Baffles, Flanges are heat treated seperately and they are welded.

Major Problems

In this section some of the defects and their remedies are explained, These defects can result from various causes. Some of them which are important and less known are discussed here :

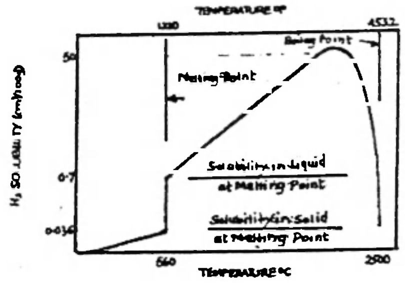


Fig 2 : Hydrogen Solubility in pure Aluminium

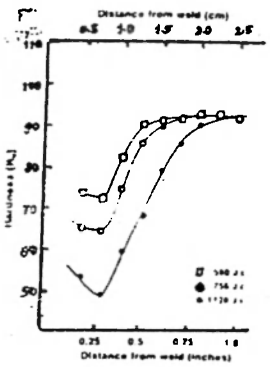


Fig 3 : Hardness profiles in 6061 - T6 TIG Weld with Various Heat Inputs

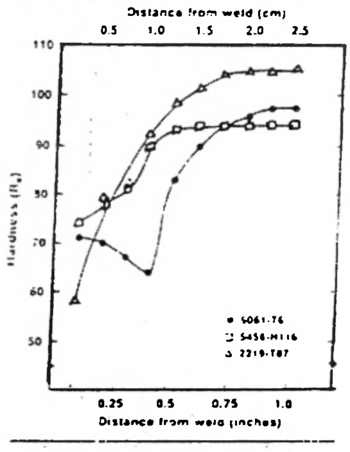


Fig 4 : Hardness profiles accross TIG Welds in Aluminium Alloys

Porosity

Porosity is very common in aluminium. This is better explained by plotting solubility v/s temperature (fig.2). This shows at higher temperature specially near M.P. there is steep rise in solubility. This is true with most of the metals. In aluminium since thermal conductivity is high weld pool solidification is fast and it does not give sufficient time for gas to escape when weld pool solidifies.

Now we must find out source of these gases specially Hydrogen. Everybody is well aware about cleanliness of joint and surrounding area. This is conventionally done by solvents like Trichloroethelene, or Acetone and wire brushing. In addition to these general techniques, there is DCRP cleaning i.e. using DCRP at low current of the order of 50-80 amps. Torch is moved all over the joint which gives bright metal surface. This also preheats the area to certain extent which is essential in Aluminium welding.

Another two new techniques which were successfully introduced are chemical and electro-chemical cleaning of filler wires and joint area. This improves surface finish in microscopic level. There is a rounding off of sharp corners hence no chance of accumulation of dust or other impurities. There is a thin uniform oxide layer formed as a result of electropolishing which prevents further oxidation/atmospheric corrosion.

Another important observation is surface finish of filler wire and smoothness of edges can reduce porosity level to great extent. Bad surface finish accumulates dust which is passed on to the weld. Also in case of MIG or AUTO TIG it gives lot of resistance in wire feeding. Lot of loose particles are produced when wire is fed through rollers. This goes into torch & blocks gas passage.

Annealing of HAZ

This is relevant only when material is welded in heat treated condition. Area in the range of 300-350° C undergoes annealing and fails at much lower strength than parent metal or weld metal (Fig. 3,4). To avoid this, either one of the following techniques can be used. :

1. Welding with low heat input.

- GMAW gives better results than GTAW.
- Fast welding speeds also improves strength but there are chances of lack of fusion.
- Wherever possible, a double operator technique is used.
- Weld in T4 i.e. in solution quench stage and then Age it to bring it to T6 condition. In this, care should be taken to weld within 24 hrs. after solution quenching as these alloys start ageing at room temperature and acquires 50-60% strength in 48 hrs. (Fig 5)
- By providing stainless steel backup ring and copper shoes either water cooled or air cooled in HAZ to absorb additional heat and quench it after welding (Fig 6).

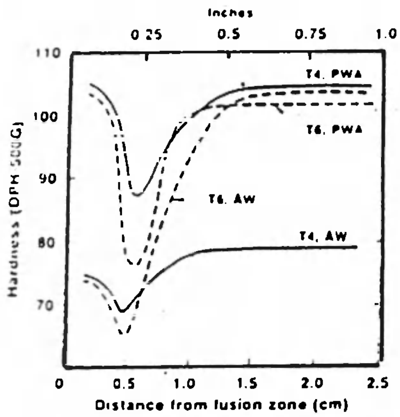
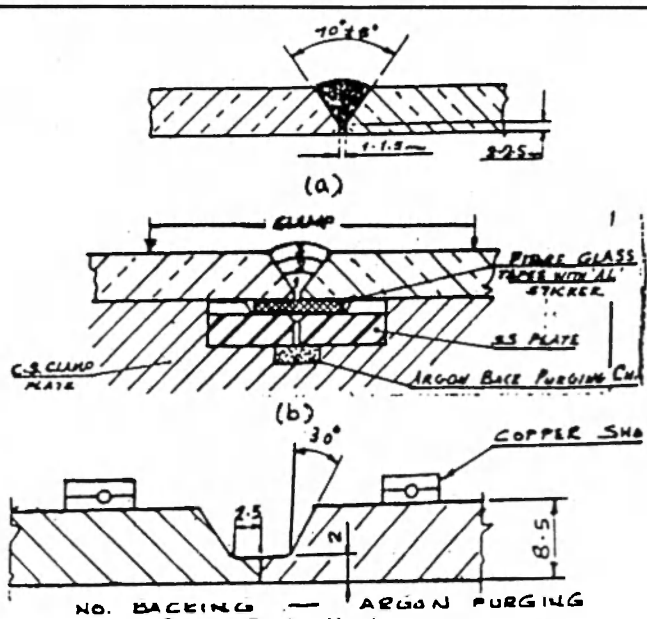


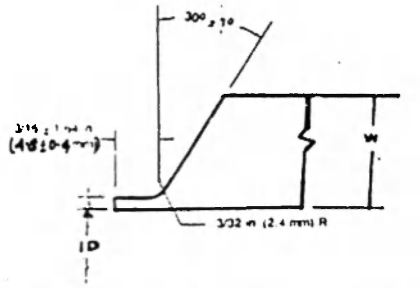
Figure 5
Hardness Profiles for 6061-T4 and T6 in the As Welded (AW) and Post Weld Aged (PWA) Conditions



Groove Design Used

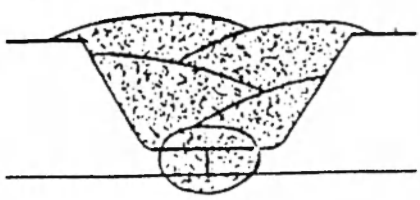
(c)

Fig. 6



Pipe Size		A		W, max	
in	mm	in	mm	in	mm
1/8 through 2 1/2	3.2 through 64	1/16 ± 1/64	1.6 ± 0.4	0.276	7.01
3 through 12	76 through 305	3/32 ± 1/64	2.4 ± 0.4	0.500	12.7

Fig: 7a



Advantages

1. Smooth, complete penetration control
2. No "suck-back"
3. No backing required
4. Good for all fixed pipe positions
5. Preheating not required

Fig 7b

Table - 2

Maximum Solid Solubilities in Aluminum of Principal Alloying Additions

Addition	Maximum Solubility (% by weight)	Temperature (°F)	Temperature (°C)
Cu	5.6	1018	546
Mg	14.9	842	450
Mn	1.3	1217	658
Si	1.6	1071	577
Zn	82.8	720	382
Mg_2Si	1.8	1103	595
$MgZn_2$	16.9	887	475

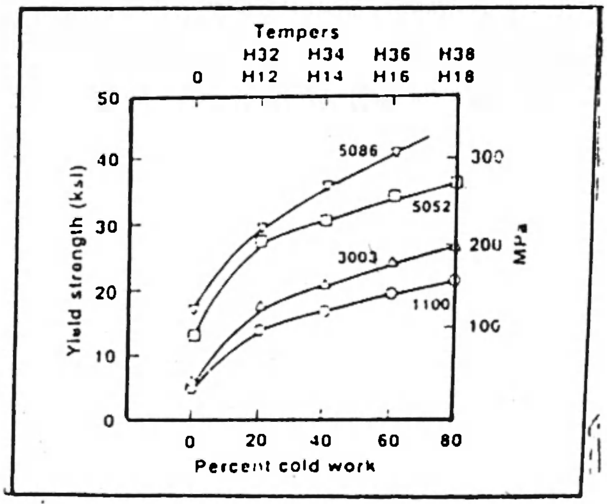


Figure 8

Effect of Cold Work on Yield Strength of Several Work-Hardening Alloys

ANNEXURE 1(A)

RECOMMENDED ALUMINIUM FILLER METALS FOR GENERAL APPLICATIONS

Base metal	319.0. 333.0 354.0.355.0. C355.0	356.0 A356.0 A357.0. 359.0 413.0,433.0	514.0.A514.0 B514.0	7005. 7039.7046. 7146. 710.0. 712.0	6070	6005.6061 6063.6101. 6151.6201. 6351.6951	5456	5454
1060. 1350	ER4145c.i.	ER4043i.f	ER4043e.i.	Er4043i	ER4043i	ER4043i	ER5356c	ER4043ei
1100.3003 Alclad 3003	ER4145c.i	ER4043i.f	ER4043e.i	ER4043i	ER4043i	ER4043i	ER5356c	ER4043e.i
2014.2024. 2036	ER4145g	ER4145	--	--	ER4145	ER4145	--	--
2219	ER4145g.c.i	ER4145c.i	ER4043i	ER4043i	ER4043f.i	Er4043f.i.	ER4043	ER4043i
3044. Alclad 3004	ER4043i	ER4043i	ER5654b	ER5356e	ER4043e	ER4043b	ER5356e	ER5654b
5005.5050	ER4043i	ER4043.i	ER5654b	ER5356e	ER4043e	ER4043b	ER5356e	ER5654b
5052.5652a	ER4043i	ER4043b.i	ER5654b	ER5356e	ER5356b.c.	ER5356b.c	ER5356b	ER5654b
5083	--	ER5356c.c.i	ER5356e	ER5183e	ER5356e	ER5356e	ER5183e	ER5356e
5086	--	ER5356c.c.i	ER5356e	ER5356e	ER5356e	ER5356e	ER5356e	ER5356b
5154.5254a	--	ER4043b.i	ER5654b	ER5356b	ER5356b.c	ER5356b.c	ER5356e	ER5654b
5454	ER4043i	ER4043b.i	ER5654b	ER5356b	ER5356b.c	ER5356b.c	ER5356b	ER5554c.e
5456	--	ER4043b.i	ER5356e	ER5556e	ER5356e	ER5356e	ER5556e	
6005.6061. 6063.6101. 6151.6201 6351.6951	ER4145c.i	ER5356c.c.i	ER5356b.c	ER5356b.ci	ER4043b.i	ER4043b.i		
6070	ER4145c.i.	ER4043e.i.	ER5356c.c.	ER5356c.c.i	ER4043e.i			
7005.7039. 7046.7146. 710.0.712.0	ER4043i	ER4043b.i.	ER5356b	ER5039e				
514.0.A514.0 B514.0	--	ER4043b.i.	ER5654b.d					
356.0.A356.0. A357.0.359.0. 413.0.443.0	ER4145c.i.	ER4043d.i.						
319.0. 333.0. 354.0.355.0. C355.0	ER4145c.d.i							

RECOMMENDED ALUMINUM FILLER METALS FOR GENERAL APPLICATIONS

ANNEXURE 1(B)

Base metal	5154 5254a	5086	5083	5052 5652a	5005 5050	3004 Alc 3004	2219	2014 2024 2030	1100 3003 Alc 3003	1060 1350
1060,1350	ER4043c.i	ER5356c	ER5356c	ER4043i	ER1100c	ER4043	ER4145	ER4145	ER1100	ER1100
1100,3003, Aclad 3003	ER4043c.i	ER5356c	ER5356c	ER4043c.i	ER4043c	ER4043c	ER4145	ER4145	ER1100	
2014,2024 2036	--	--	--	--	--	--	ER4145g	ER4145g		
2219 3604	ER4043i	ER4043	ER4043	ER4043i	ER4043	ER4043	ER2319c.l.i			
Alclad 3004	ER5654b	ER5356c	ER5356e	ER4043c.i	ER4043c	ER4043c				
5005,5050	ER5654b	ER5356c	ER5356c	ER4043c.i	ER4043d.c.					
5052,5652a	ER5654b	ER5356e	ER5356e	ER5654a.b.c						
5083	ER5356c	ER5356c	ER5183c							
5086	ER5356b	er5356e								
5154,5254a	ER5654a.b									

a. Base metal alloys 5254 and 5652 are sometimes used for hydrogen peroxide service. ER 5654 filter metal is used welding both alloys for service at 150oF and below.

b. ER 5183, ER5356, ER5554, ER5556 and ER5654 may be used. In some oases they provide : (1) improved color match after anodizing treatment. (2) highest weld ductility and (3) higher weld strength. ER5554 is suitable for elevated temperature service.

c. ER4043 may be used for some applications.

d. Filler metal with the same analysis as the base metal is sometimes used.

e. ER5183, ER5356 or ER5556 may be used.

f. ER4145 may be used for some application.

g. ER2319 may be used for some application

i. ER4047 may be used for some applications

j. ER1100 may be used for some applications

Notes :

1. Service conditions such as immersion in fresh or water, exposure to specific chemicals, or a sustained high temperature (over 150°F) may limit the choice of filler metals. Filler metals ER5356, ER5183, ER 5556 and ER 5654 are not recommended for sustained temperature service.
2. Recommendations in this table apply to gas shielded arc welding process. For oxyfuel gas welding, only ER1100, ER4043, ER4047 and ER4145 filler metals are ordinarily used.
3. Filler metals are listed in AWS Specification A5. 10-80.
4. Where no filler metal is listed, the base metal combination is not recommended for welding.

ANNEXURE - 2

COMPOSITIONS AND APPLICATIONS OF NONHEAT-TREATABLE WROUGHT ALLOYS

Aluminium Association Designation	Nominal Compositions (% Alloying Elements) Cu	Mn	Mg	Cr	Typical Applications
1060	99-6% min. aluminium				Chemical process equipment, tanks, piping
1100	99.0% min. aluminium				Architectural and decorative applications, furniture, piping deep drawing applications, spun hollow ware
1350	99.5% min. aluminium				Electrical conductor wire Dus conductor
3003	0.12	1.2	--	--	General Purpose applications where slightly higher strenght than 1100 is required Process and food handling equipment chemical and petroleum drums and tanks.
3004	--	1	1.0	--	Sheet metal requiring higher strength than 3003. Rooting siding, gutters, pressure vessels and irrigation tubing.
5005	--	--	0.8	--	Electrical conductor and architectural applications.
5050	--	--	1.4	--	Similar to 3003 and 5005 but stronger. Has excellent finishing qualities.
5052 5652	--	--	2.5	--	Sheet metal applications recurring higher strength than 5050. Formable and good corrosion resistance Storage tanks, boats, appliances. etc. Alloy 5652 is a higher purity version for H_2O_2 service.
5083	--	0.7	4.4	0.15	Structures, tanks, unfired pressure vessels, manne components, railroad cars, cryogenics, drilling figs.
5088	--	0.45	4.0	0.15	Marine components tanks tankers, truck, frames
5154 5254	--	--	3.5	0.25	Unfired pressure vessels, tankers, Alloy 5254 as a hinger purity version suitable for H_2O_2 service.
5451	--	0.8	2.7	0.12	Structural applications and tanks for sustained high temperature service.
5456	--	0.8	5.1	0.12	Structures tanks unfired pressure vessels marine components.

ANNEXURE - 3

NOMINAL COMPOSITIONS OF COMMON WELDABLE WROUGHT ALUMINIUM ALLOYS (PERCENT BY MASS)

Alloy	Cu	Mg	Mn	Si	Zn	Cr	Zr	Ti	Al
1060	--	--	--	--	--	--	--	--	99.60 min
1100	0.12	--	--	--	--	--	--	--	99.00 min
1350	--	--	--	--	--	--	--	--	99.50 min
2219	6.3	--	0.30	--	--	--	0.18	0.06	Remainder
3003	--	--	1.25	--	--	--	--	--	Remainder
3004	--	1.0	1.25	--	--	--	--	--	Remainder
5052	--	2.5	--	--	--	0.25	--	--	Remainder
5454	--	2.7	0.75	--	--	0.12	--	--	Remainder
5083	--	4.45	0.7	--	--	0.15	--	--	Remainder
5086	--	4.0	0.45	--	--	0.15	--	--	Remainder
5456	--	5.1	0.75	--	--	0.12	--	--	Remainder
6101	--	0.6	--	0.50	--	--	--	--	Remainder
6061	0.27	1.0	--	0.6	--	0.20	--	--	Remainder
6063	--	0.7	--	0.40	--	--	--	--	Remainder
7004	--	1.5	0.45	--	4.2	--	0.15	--	Remainder
7005	--	1.4	0.45	--	4.5	0.13	0.14	--	Remainder
7039	--	2.8	0.25	--	4.0	0.20	--	--	Remainder

ANNEXURE 4

NOMINAL COMPOSITIONS OF COMMON ALUMINIUM FILLER ALLOYS (PERCENT BY MASS)

Alloy	Si	Cu	Mn	Mg	Cr	Ti	V	Zr	Al
1100	--	0.12	--	--	--	--	--	--	99.00 min
1188	--	--	--	--	--	--	--	--	99.88 min
2319	--	6.3	0.30	--	--	0.15	0.10	0.17	Remainder
4009	5.0	1.25	--	0.50	--	--	--	--	Remainder
4010	7.0	--	--	0.35	--	--	--	--	Remainder
4011	7.0	--	--	0.55	--	0.12	--	--	Remainder
4043	5.2	--	--	--	--	--	--	--	Remainder
4047	12.0	--	--	--	--	--	--	--	Remainder
4145	10.0	4.0	--	--	--	--	--	--	Remainder
4643	4.1	--	--	0.20	--	--	--	--	Remainder
5183	--	--	0.75	1.7	0.15	--	--	--	Remainder
5356	--	--	0.12	5.0	0.12	0.13	--	--	Remainder
5554	--	--	0.75	2.7	0.12	0.12	--	--	Remainder
5556	--	--	0.75	5.1	0.12	0.12	--	--	Remainder
5654	--	--	--	3.5	0.25	0.10	--	--	Ramainder
206.0	--	4.6	0.35	0.25	--	0.22	--	--	Remainder
C355.0	5.0	1.25	--	0.50	--	--	--	--	Remainder
A 356.0	7.0	--	--	0.35	--	--	--	--	Remainder
357.0	7.0	--	--	0.52	--	--	--	--	Remainder
A357.0	7.0	--	--	0.55	--	0.12	--	--	Remainder

- By selecting a edge preparation by which total heat input can be reduced (Fig 7).

CRAKS

Cracks can occur if :

- Selection of filler wire is wrong. (refer annexure - 1.5)
- Sudden quenching due to improper preheat and post heat.
- Grinding duct embodied in edges to be welded. Do not grind aluminium, use chipper or rotary burr wheels for gouging and edge preparation.
- Fixture should be designed in such a way that it will take care of expansion of contraction.

CONCLUSION

Aluminium alloys specially high strength alloys are certainly difficult to weld considering their end use or weldability to get required properties. But at the same time if proper sequence, technique and care is exercised it is not impossible to weld them.Techniques which are developed are mainly used for aluminium 6061 type of alloys and results are proven and definitely better and near the required values. Same technique is now being applied for 2xxx & 7xxx series of alloys. Many of these properties also depends upon cleanliness and refining of base metal and filler wires. Only matching of wire or weld chemistry of specified elements is not important but effective refining, certain amount of deoxidisers like titanium or ziroconium and degassing are also important. Control on impurities which form low melting point alloys are also to be considered before accepting an alloy.Table-2 shows maximum solid solubilities in aluminium of principal alloying elements. There are some alloys which age at room temperature at much faster rate and acquire almost full strength in 24-48 hrs. need to be stored at temperature close to zero or subzero. Some of the aluminium alloys can be strengthened by cold working (Fig-8) which loose strength because of welding heat.