Partially Melted Zone in Dissimilar Aluminium Alloy Welds-Effect of Prior Thermal Temper and Welding Process

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ABSTRACT

Partially melted zone (PMZ) of aluminium alloy welds is an important region and requires careful attention. This is mainly because PMZ in these alloys is a weak link in the weldments and is significantly affected by welding parameters. Microstructural changes in PMZ are related not only to welding heat input and processes, but also depend on the initial thermal history of the alloy (for example, whether it is in O, T4, T6 or T87 condition etc.). Interestingly not many detailed studies are available in this respect. In the present work effect of prior thermal temper and welding process on the PMZ behaviour of dissimilar AA2014 and AA6061 alloy GTA and EB welds were studied. Grain coarsening and melting in PMZ is more when the alloys are welded in T4 temper than in O condition and AA2014 alloy is prone for liquation compared to AA6061 alloy which attributes high alloying element concentration in AA2014 side of the joint. EB welding proved to be efficient welding process compared to GTA welding in terms of resistance to liquation and better mechanical properties

Keywords: Partially Melted Zone, Gas Tungsten Arc Welding, Electron Beam Welding, Dissimilar alloy welds

INTRODUCTION

Welding of dissimilar aluminium alloys is gaining importance in industry, since it facilitates the design of complex lightweight structures at minimum cost and having minimum weight [1]. For example, in transportation equipment extruded AA 6000 series alloys are welded to AA 5000 series alloy rolled plates and to case AA 4000 series alloy components [2].

The major problem in dissimilar alloy welding results from the differences in physical properties of the base alloys, such as melting point, thermal conductivity and coefficient of thermal expansion. The differences in thermal conductivity result in different heat input requirements for the individual alloys. For example, for a given thickness and travel speed of the welding torch, AA6060 (high thermal conductivity) alloy must be welded using a higher arc current than AA 5083 (low thermal conductivity) alloy. The heat produced by the arc will flow more rapidly in the material having higher thermal conductivity. This can lead to inadequate fusion in the high thermal conductivity alloy or excessive melting, resulting in burn through in the low thermal conductivity alloy [3]. Furthermore, the filler metal requirements (dependent on the chemical composition of the base alloy) can be significantly different for the individual base alloys.

The partially melted zone (PMZ) is the area immediately outside the weld metal where the liquation can occur during welding because of heating above the eutectic temperature. Intermetallic phases present in the aluminum alloys induce liquation that can occur partially along the grain boundary (GB) as well as in the grain interior. This GB liquation can make PMZ weak and may lead to intergranular cracking under the tensile strains developed during welding. The heat treatable aluminium alloys are known to be susceptible to cracking in the PMZ area of the weld.

Huang and Kou recently studied PMZ liquation in the Gas metal arc welds of alloys AA2219, AA2024, AA6061 and AA7075, including the liquation mechanisms and found that significant weakening of the PMZ is caused by GB segregation [4-7]. Liquation and liquation-induced hot cracking in aluminium alloys AA2024, AA6061 and AA7075 have been studied and attention appeared to have been focused much more on the liquation-induced hot cracking than liquation itself [8-18]. Detailed studies on the effect of prior thermal temper and on the PMZ behavior of heat treatable aluminium alloys are not available in the literature.

In the present work, efforts are made to study the influence of prior thermal temper and welding process on PMZ behaviour of dissimilar (i.e. an alloy welded to a different alloy) medium strength aluminum alloys. One of the two alloys selected was an Al-Cu based alloy i.e. AA2014. The other alloy selected was an Al-Mg-Si based alloy known as alloy AA6061. Alloy AA2014 is selected because it is essentially a binary alloy of Al-4.5% Cu and its microstructure is therefore fairly easy to understand. AA6061 is selected because it is essentially a ternary alloy of Al-Mg-Si and liquation susceptible during welding. The present investigation aims at finding out variation in the microstructure and hardness of PMZ of GTA and EB welds of AA2014 and AA6061 alloys with initial thermal tempers of O and T4.

EXPERIMENTAL DETAILS Wrought AA2014 and AA6061 alloy plates of thickness 4 mm were used in the present study in O (mill annealed) and T4 (Solution heat treated at 540OC for 1 hr, quenched and aged for 30 days at room temperature) conditions. The chemical composition of the base metals and filler are given in the Table.1. Alternate current gas tungsten arc welding (GTAW) and electron beam welding (EBM) processes were used to weld the alloys. AA4043 filler is being used in GTA welding. Autogenous onbead welds were made in EB welding process. Details of the welding parameters used are given in Table 2. The samples of base metal and welds with PMZ were polished on emery papers and disc cloth to remove the very fine scratches. Polished surfaces are etched with Keller's reagent. Schematic of the locations on the weld, where the PMZ microscopy was done is shown in Fig.1. Optical, SEM and EDX studies have been carried out on the welds. The prior thermal conditions are referred in all figures and text as O and T4 with an aim to study the influence of prior thermal temper and welding process on the PMZ of dissimilar aluminium alloy welds. The microstructures were recorded with image analyzer attached to the Metallurgical microscope. The SEM micrographs were taken with secondary electron image at 15kV and 20 kV. Energy dispersive X-ray analysis (EDAX) has been carried out to quantify the elements of Si, Mg, Cu, Fe and Mn using ZAF software. Vickers hardness testing has been carried out on weld, PMZ and HAZ regions of the samples with 5 kgf load. Nearly 10 to 12 readings were taken. The range of hardness values was reported and given in the Tables 6 and 7.

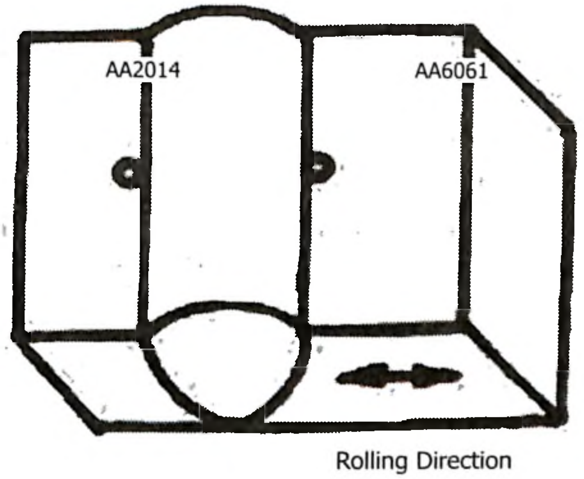


Fig. 1 : Location of the PMZ where the photomicrographs are taken

Table - 1 Chemical compositions of the base materials & filler material (Wt%)									
Material	Cu	Mg	Si	Fe	Mn	Cr	Zn	Ti	Al
AA 2014 (BM)	4.5	0.4	0.8	1.0	0.8	0.1	0.25	0.15	Bal
AA 4043 (Filler metal)	0.25	0.05	5.2	0.8	0.05	--	--	--	Bal
AA6061	0.31	0.69	0.53	0.23	0.33	---	----	--	Bal

Table-2 Welding parameters used

Welding process	Welding current (Amp)	Voltage (V)	Welding speed (mm/min)	Gas flow rate (1/min)	Filler material	Filler feed rate (mm/min)
GTA	385	7.2	200	16	AA4043	2200
EB	0.051	50,000	1000	Vacuum	None	--

RESULTS AND DISCUSSION

Base metal studies

AA2014

Optical and SEM micrographs of the base metal AA2014 in O and T4 conditions are shown in Fig. 2. Microstructure consisted of white matrix of α-solid solution grains and second phase eutectics (α + Al_2Cu) appearing black in colour. The grains are equiaxed in annealed condition and elongated in T4 temper. Large eutectics are present both within the grains and at the grain boundaries. The solution heat treating temperature for AA2014 is 540°C and the base metal is expected to consist of α-matrix plus additional undissolved θ (Al_2Cu) particles [19-20]. During solution treating of the ingot, the large eutectic islands decompose into θ particles and dissolve in to α-matrix. During rolling of ingot into plates or sheets, some of the large θ particles are displaced or even fractured. Optical and SEM photographs of the present study clearly reveal that the density of second phase particles in T4 of AA2014 is less than that of O condition.

AA6061

Average composition of the base metal is given in Table 1. The available silicon for forming Mg_2Si is calculated as (21) and it is 0.39Wt%.

Available Silicon = % Si ¼ (% Fe + % Mn)

Amount of inclusions (0.71Wt%) and dispersiods (1.04Wt%) present in the alloy estimated from the composition. It is assumed that all the available manganese forms into dispersiods ($Al_{12}MnSi$) and all the iron forms into inclusions(Fe_3SiAl_{12}). X-ray diffraction studies made on this alloy shown high intensity aluminum peak observed on (200) planes indicating texture in the alloy (Fig. 3). The alloy was dissolved in sodium hydroxide and the undissolved particles were filtered, dried and then subjected to x-ray diffraction. The phases Mg_2Si and Fe_3SiAl_{12} were identified from the diffraction pattern

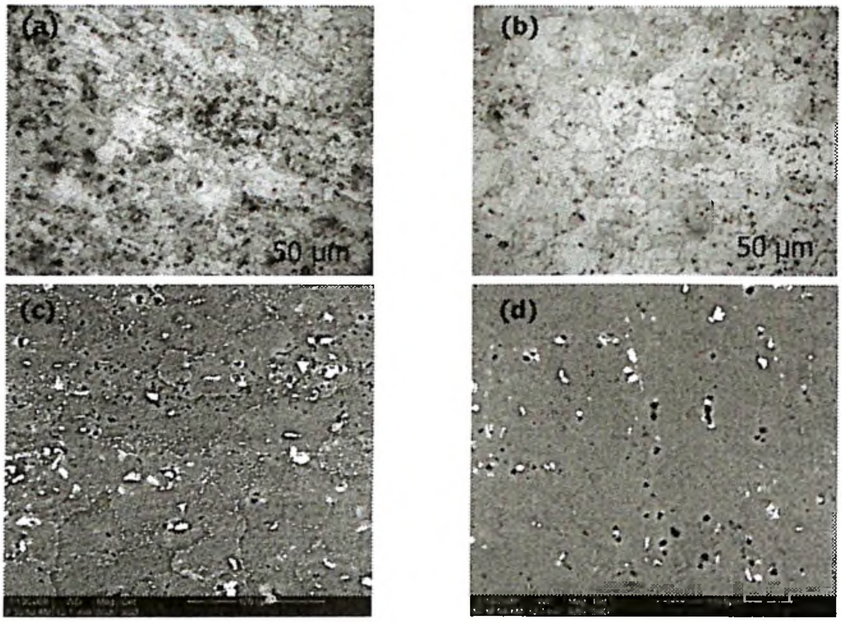


Fig. 2 : Micrographs of base metals AA2014
(a) Optical of O (b) Optical of T4 (c) SEM-BSE of O (d) SEM-BSE of T4

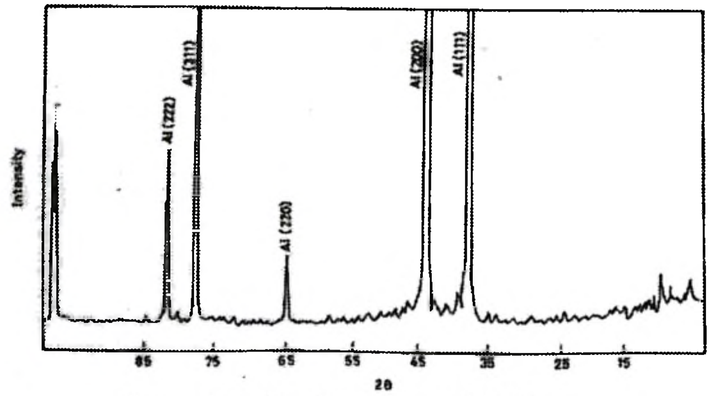


Fig. 3 : X-ray diffraction pattern of AA 6061 alloy

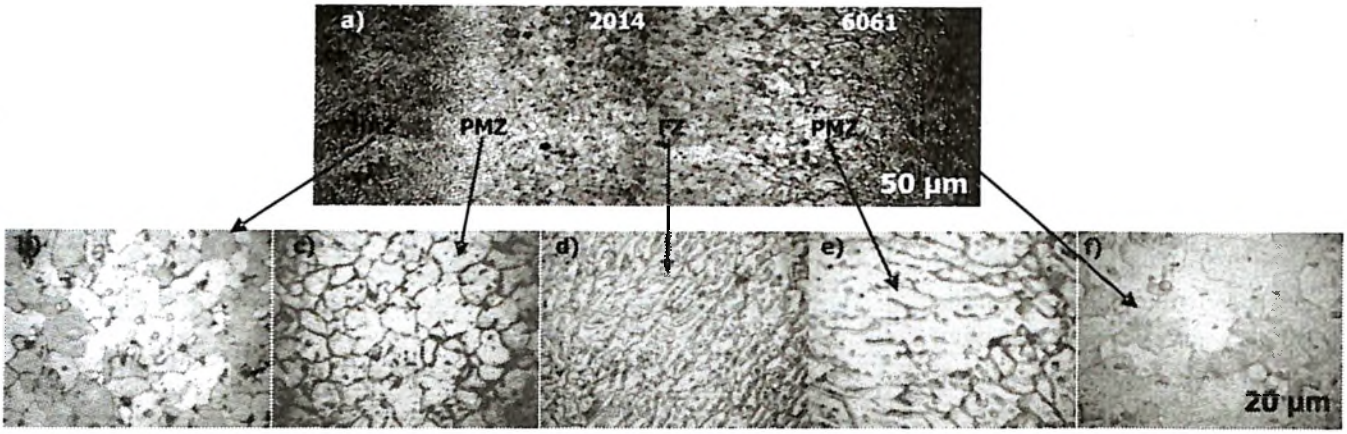


Fig. 6: Optical microstructures of 2014(T4)-6061(T4) GTA weld
a) FZ+PMZ+HAZ b) HAZ (2014) c) PMZ (2014)
d) FZ e) PMZ (6061) f) HAZ (6061)

AA 6061 side of the joint

In AA6061 alloy also the PMZ was observed near fusion line and is as shown in Figs. 7 and 8. Coarsened grain boundaries occurred adjacent to the fusion line. Coarsening of grain boundaries indicated partial melting of the AA6061 alloys. Optical micrographs show clearly dark etched grain boundaries indicating liquation in the PMZ. The grain boundary filled with eutectic liquid was also seen in optical and SEM micrographs. In general Al liquids that are richer in Si are considered to be more fluid. Therefore penetration should be easier for the AA4043 filler and the lower solidus temperature of the AA4043 might have promoted liquid penetration into the HAZ for a longer distance [16]. The possible eutectic reactions causing liquation in PMZ of the welds of AA6061 are as follows [22]

i) $\alpha + Si \longrightarrow L$ at 577°C

ii) $\alpha + Mg_2Si + Si \longrightarrow L$ at 555°C

Effect of welding process on the liquation in PMZ

The width of thick etched PMZ was measured with help of micrometer inserted in microscope. The width of PMZ was found to vary with the heat input and welding technique. The width of PMZ appears to be lower in case of EB welding (40µm) compared to GTA welding (75µm) as shown in Figs.7 and 8. This is attributed to the low heat input, high heat intensity with fast cooling rates associated in EB welding.

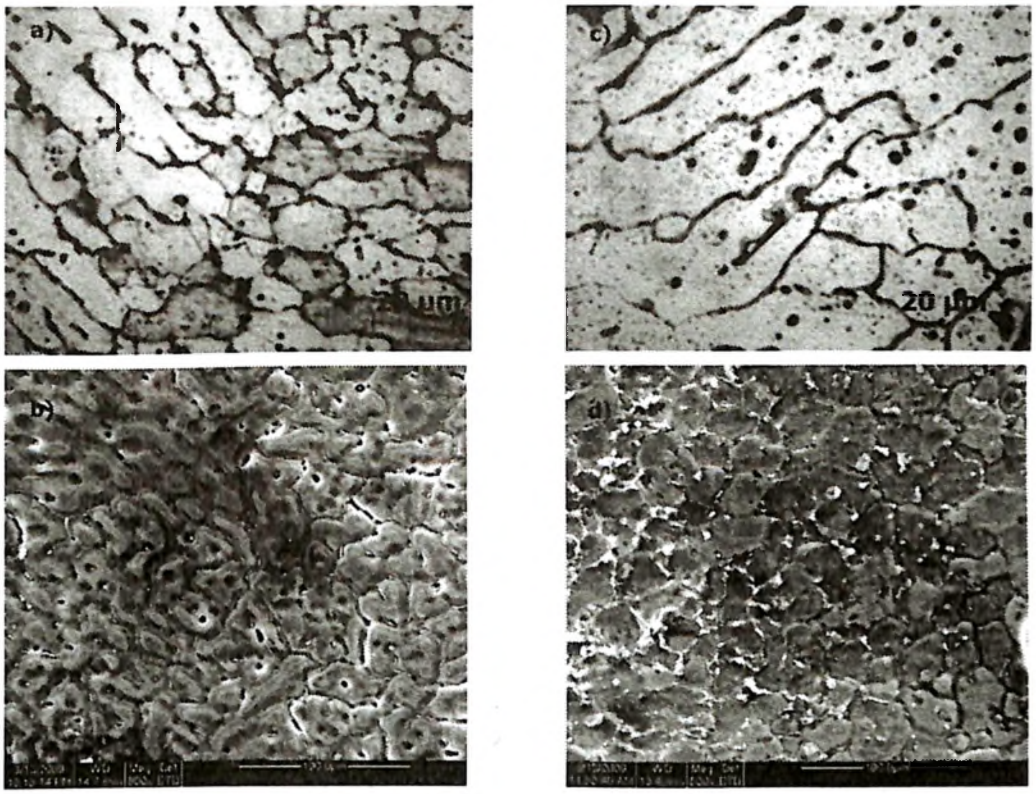
The SEM-EDX values of two randomly selected points in PMZ at eutectic grain boundary (P1) and α-matrix (P2) are taken and these values are given in Tables 3 and 4 for GTA and EB welds respectively. Enrichment of elements like Copper and silicon at the grain boundaries is observed.

Effect of prior thermal temper on liquation in PMZ

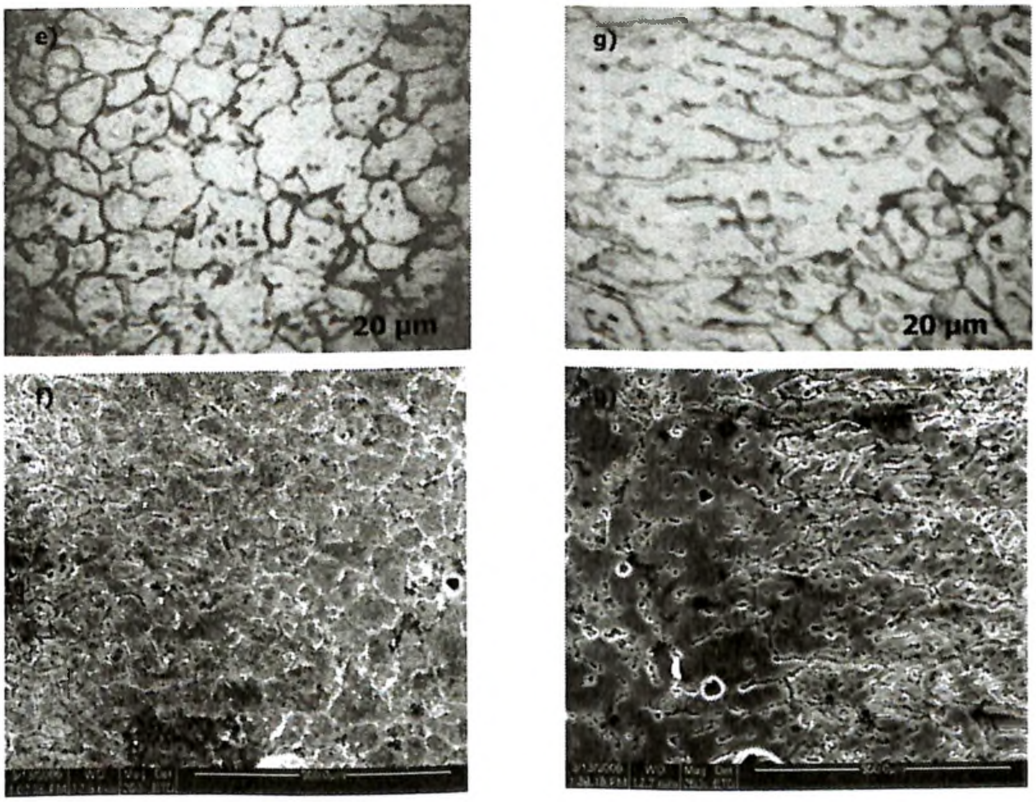
The prior thermal temper (T4) condition of the base metals modified the microstructure of the PMZ both in GTA and EB welding processes (Figs. 7 and 8). Coarsening of the eutectics is more in O condition than in T4 condition. This may be attributed to large volume fraction of coarser precipitates that would be present in O condition than in T4 condition on liquation and subsequent solidification along the grain boundaries.

Hardness studies

Hardness survey across the weld joint was done and the range of the hardness values is shown in Tables 5 and 6. It is noticed that the hardness of the PMZ is more than that of the HAZ which is attributed to the precipitation of the eutectics in PMZ and depletion of eutectics in HAZ during welding. This causes the HAZ softening. Similarly it is noticed that the hardness of PMZ was high in EB welds when compared to GTA welds. This is attributed to high heat intensity and cooling rates associated in EB weld. Hardness data also confirms the microstructural observations of the PMZ and HAZ regions of the welds. More hardness values were observed in T4 condition than in O condition.

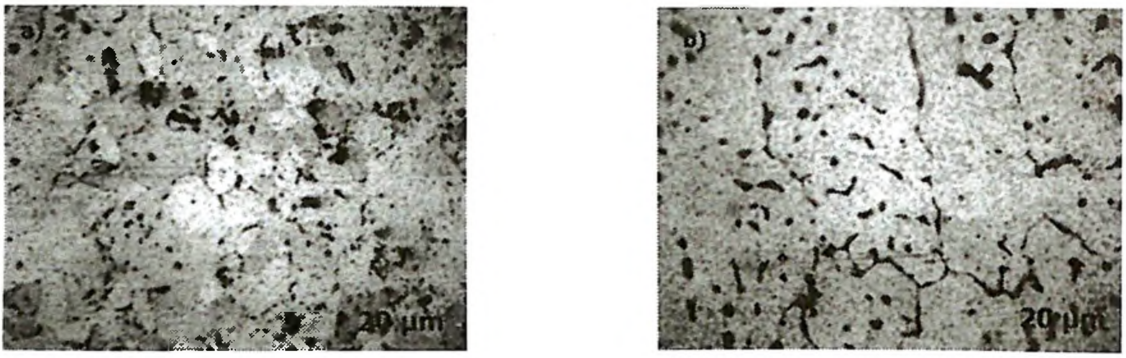


2014 (O) - 6061 (O) a & b : 2014 size c & d : 6061 size

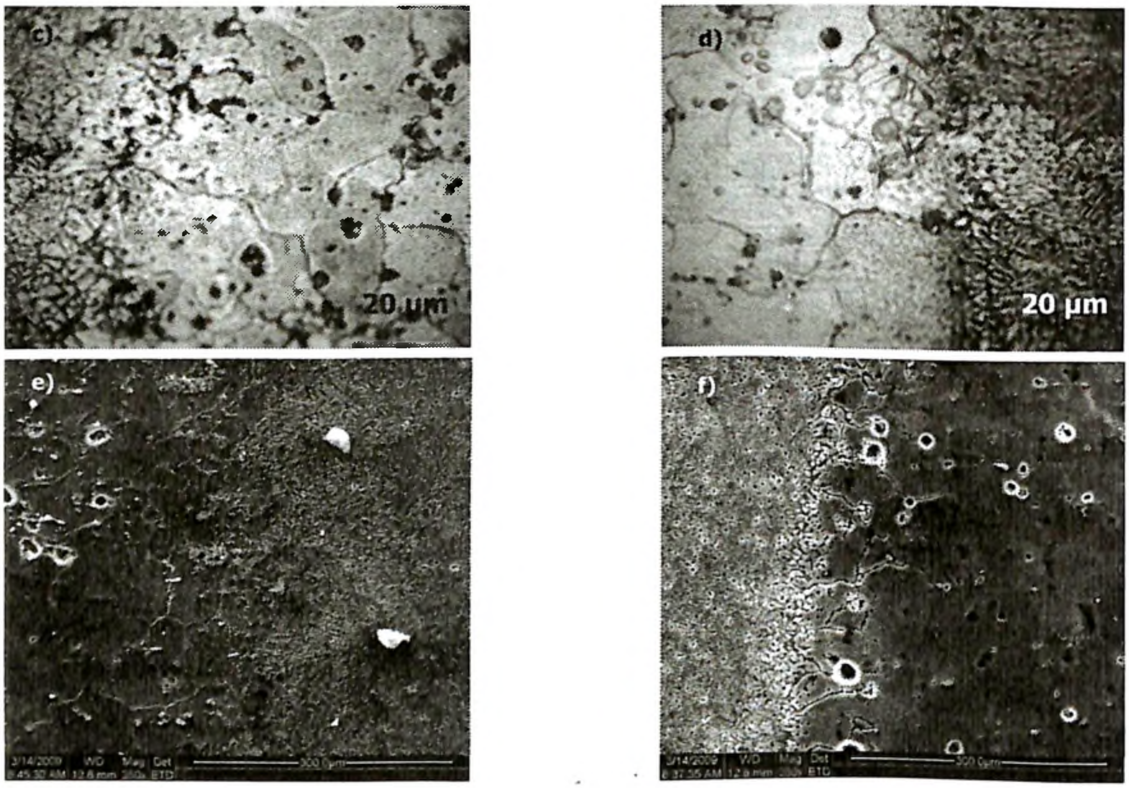


2014 (T4) - 6061 (T4) e&f : 2014 size g&h : 6061 size

Fig. 7 : Optical and SEM micrographs of PMZ of GTA welds



2014 (O)-6061(O) (a) 2014 size (b) 6061 size



2014 (T4)-6061(T4) c & e : 2014 size d & f : 6061 size

Fig. 8 : Optical and SEM micrographs of PMZ in EB welds

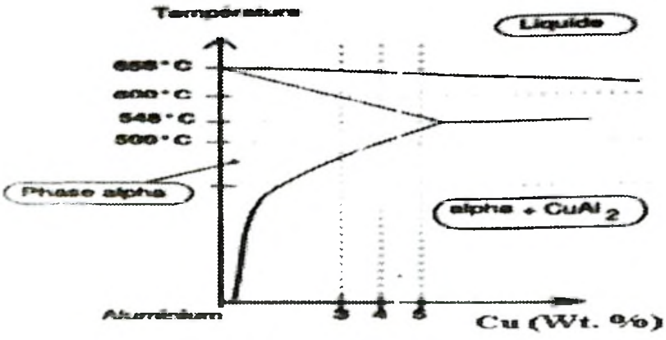


Fig. 9 : Al-Cu phase diagram

Table-3 Composition (Wt. %) of particles in PMZ (SEM-EDAX)

GTAW AA2014(O)-AA6061(O)								
	AA2014 SIDE				AA6061 SIDE			
	Mg	Cu	Si	Al	Mg	Cu	Si	Al
P1 (GB)	1.42	14.70	10.93	59.52	03.65	01.84	13.95	76.44
P2 (Matrix)	2.08	2.19	1.81	93.05	03.01	01.19	03.46	90.77
GTAW AA2014(T4)-AA6061(T4)								
P1(GB)	01.01	11.05	16.62	71.32	03.94	15.75	08.58	71.73
P2 (Matrix)	01.47	00.78	01.12	96.63	01.51	02.29	01.03	95.17

Table-4 Composition (Wt. %) of particles in PMZ (SEM-EDAX)

EBW AA2014(T4)-AA6061(T4)								
	AA2014 SIDE				AA6061 SIDE			
	Mg	Cu	Si	Al	Mg	Cu	Si	Al
P1(GB)	01.57	09.49	01.11	87.03	01.61	01.73	05.35	72.61
P2 (Matrix)	01.12	03.19	00.80	94.89	01.85	--	--	98.15

Table-5 Vickers hardness value ranges of AA2014 (O)-AA6061 (O)

	AA2014		AA6061	
Welding process	PMZ	HAZ	PMZ	HAZ
GTAW	100-110	71-78	62-66	55-65
EBW	115-125	95- 106	70-78	68-75

Table-6 Vickers hardness value ranges of AA2014 (T4)-AA6061 (T4)

	AA2014		AA6061	
Welding process	PMZ	HAZ	PMZ	HAZ
GTAW	108-116	80-97	71-75	60-69
EBW	127-136	109-120	80-87	70-78

CONCLUSIONS

1. Eutectic reaction of excess silicon rich particles with surrounding α-matrix and back filling of silicon rich liquid from the weld pool in AA6061 alloys and eutectic reaction of excess copper rich particles with surrounding α- matrix and back filling of copper rich liquid from the weld pool in AA2014 alloys causes liquation in dissimilar welds of alloys AA6061-AA2014.
2. Electron beam welding is proved to be the efficient welding process than the GTA welding interms of resistance to liquation and better mechanical properties.
3. It is noticed that there is diffusion of alloying elements from high concentration to low concentration across the dissimilar weld joints.
4. Prior thermal temper plays important role in the liquation of partially melted zone of the heat treatable aluminium alloy Welds.

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