Effect of Post Weld Heat Treatment on Corrosion Behavior of AA2014 Aluminum – Copper Alloy Electron Beam Welds

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Abstract. The present work pertains to the study of corrosion behavior of aluminum alloy electron beam welds. The aluminum alloy used in the present study is copper containing AA2014 alloy. Electron Beam Welding (EBW) was used to weld the alloys in annealed (O) condition. Microstructural changes across the welds were recorded and the effect of post weld heat treatment (PWHT) in T4 (Solutionized and naturally aged) condition on pitting corrosion resistance was studied. A software based PAR basic electrochemical system was used for potentiodynamic polarization tests. From the study it is observed that weld in O condition is prone to more liquation than that of PWHT condition. This may be attributed to re-melting and solidification of excess eutectic present in the O condition of the base metal. It was also observed that slightly higher hardness values are recorded in O condition than that of PWHT condition. The pitting corrosion resistance of the PMZ/HAZ in PWHT condition is better than that of O condition. This is attributed to copper segregation at the grain boundaries of PMZ in O condition.

1. Introduction

Addition of alloying elements like copper, magnesium and silicon significantly contributes to strength of aluminum alloys by precipitation hardening. The limited solubility of these elements in aluminium leads to distribution of these alloying elements not only in the aluminum solid solution, but also in fine precipitates and coarse intermetallic particles. These particles, viz., CuAl2 and Mg2Si are crucial in playing a key role in the welding of heat treatable aluminum alloys and mainly they may induce liquation in the partially melted zone (PMZ). The heat treatable aluminum alloys are known to be susceptible to cracking in the PMZ area of the weld. Huang and Kou studied the effect of PMZ liquation in the gas metal arc welds of alloys AA2219, AA2014, AA6061 & AA7075 including the liquation mechanization and they found that significant weakening of PMZ is due to grain boundary segregation[1-4]. Even though the preferred welding method for aluminum alloys is alternating current GTA welding process, various investigators have identified several advantages and disadvantages of the pulsed current technique [5-7]. By keeping in view the problems of fusion welding of medium strength aluminum alloy AA2014, electron beam welding is...
used. Aim of present work is to compare the microstructural changes and corrosion behavior of the welds when this alloy is welded by electron beam welding process in O and T4 conditions.

2. Experimental Details

Wrought AA 2014 alloy (4 mm thick) was welded in annealed (O) condition. The composition of the alloy used in the present investigation is given in Table 1. Electron Beam Welding (EBW) process was used to weld the plates. Details of the welding parameters used are given in Table 2. Prior to welding, the base material coupons were brushed and thoroughly cleaned with acetone. After welding, the samples were post weld heat treated under T4 (solutionizing treatment at 540°C for 1 hour and aged at room temperature for 30 days) condition. The samples of base metal and welds in both O and PWHT conditions with PMZ were polished on different grade of emery papers and disc cloth to remove the very fine scratches. After polishing, the surfaces were etched with Keller's reagent. The microstructures were recorded with Olympus made optical metallurgical microscope attached with Image analyze software. Vickers hardness testing was carried out in all regions of the weld viz. fusion zone, PMZ and HAZ regions of the samples with 5 kg load and 15 seconds dwelling time. In the present study dynamic polarization studies were conducted in 3.5% NaCl solution. The pH of NaCl solution was adjusted to 10 by adding potassium hydroxide and this higher pH was mainly to obtain the polarization curve with sharp active-passive transition. Optical micrographs of the joint after corrosion were taken with image analyzer attached to metallurgical microscope.

| Table 1 Chemical compositions of the base and filler materials used |
|-----------------|---|---|---|---|---|---|---|---|
| Material | Cu  | Mg  | Si  | Fe | Mn | Cr  | Zn   | Ti  |
| AA2014 | 4.5 | 0.4 | 0.8 | 0.7 | 0.8 | 0.1  | 0.25 | 0.15 |
|         |     |     |     |    |    |      | Balance |

| Table 2 Parameters used in Electron beam welding |
|-----------------|---|---|---|---|
| Welding process | Welding current (Amp) | Voltage (V) | Welding speed (mm/min) | Gas flow rate (l/min) |
| EB | 0.051 | 50,000 | 1000 | Vacuum |

3. Results and Discussion

3.1 Microstructure studies

3.1.1 Base Metal

In aluminium alloys the formation of intermetallic phases and precipitates depend mainly on the chemical composition of the alloy. The basic condition of the alloy chosen affects size and distribution of these phases. Optical microscopy, XRD, SEM-EDX and TEM were used to characterize the microstructures of base metals. Optical micrographs of the base metal AA2014 in O and T4 conditions are shown in Fig. 1. The microstructural show white matrix of α-solid solution grains and the second phase particles appearing as black in color. Microstructures of the base metals clearly reveals that relatively fine and uniformly distributed eutectics are present in T4 condition, where as coarse and non-uniformly distributed eutectics in O condition. SEM micrographs of base metal AA2014 in O and T4 conditions are shown in Fig. 2. Quite large particles (2-10μm) were present both within grains and at grain boundaries. Energy dispersive X-ray analysis (EDX) values of some randomly chosen particles indicated that Al/Cu weight ratios of these particles was close to that of about 53/47 for θ (Al₂Cu). The typical EDX spectrum of the particle is shown in Fig. 3.
Fig. 1 Optical micrographs of base metal AA2014 (a) O condition (b) T4 condition

Fig. 2 SEM micrographs of base metal AA2014 (a) O condition (b) T4 condition

Fig. 3 EDX spectrum of AA2014-T4 particle
These particles will be considered as the θ phase as an approximation, even though they may contain very small amounts of other elements as well. Though they appear several small particles within the grains and along the grain boundaries (GBs), they were believed to be θ phase, as they were too small to be analyzed by SEM-EDX.

It is already proved that the eutectic liquid during the terminal stage of solidification in ingot casting solidifies and forms large and small eutectic particles along the grain boundaries and within grains. The solution heat-treating temperature for AA2014 alloy is 540°C. From the Al-Cu phase diagram [Fig. 4] the base metal is expected to consist of α-matrix plus additional undissolved θ (CuAl2) particles (8).

![Fig. 4 Al-Cu phase diagram](image)

### 3.1.2 Electron Beam Welds

Optical micrograph of fusion zone in AA2014 electron beam welds is shown in Fig. 5. The microstructure of fusion zone in O condition [Fig. 5a] revealed the fine grains of CuAl2 eutectics appearing in the dendritic matrix of α-solid solution. The eutectics are present within the grains and along the grain boundaries. The eutectics are formed as thick and continuous network in the fusion zone. It is indicated from the optical micrograph of FZ of AA2014 EB welds in PWHT condition [Fig. 5b] that the thickness of the grain boundary eutectics was reduced after PWHT and the grains were coarsened.

![Fig. 5 Optical micrograph of fusion zone of AA2014 EB welds in a) O condition b) PWHT condition](image)

The partially melted zone (PMZ) is in the narrow region immediately outside the fusion zone, where the maximum temperature experienced during welding ranges from the liquidus temperature of about 642°C on the fusion zone side to the eutectic temperature of 548°C on the base metal side.
The optical micrographs of PMZ of AA2014 welds both in O and PWHT conditions are shown in Fig. 6. The dark etched thin boundary between fusion zone and heat affected zone is the evidence of liquation in partially melted zone. It is observed from the optical micrograph of PMZ of similar AA2014 EB welds in PWHT condition [Fig. 6b] that the thickness of the grain boundary eutectics was reduced after PWHT and the grains are modified as equi-axed grains. The liquation in PMZ was also reduced after PWHT. Hence it is concluded that weld in O condition [Fig. 6a] is prone to more liquation than that of PWHT condition. This may be attributed to re-melting and solidification of excess eutectic present in the O condition of the base metal.

![Optical micrographs of PMZ in AA2014 EB welds (a) O condition (b) PWHT condition](image)

**Fig. 6 Optical micrographs of PMZ in AA2014 EB welds (a) O condition (b) PWHT condition**

### 3.2 Hardness studies

The intent in evaluating the base material hardness in the current work is to have a base line for comparison with weld hardness. The hardness values of base metal, FZ, PMZ and HAZ in AA2014 EB welds in O and T4 conditions are given in Tables 3 and 4. It is observed from Table 3 that the hardness values of base metals are higher in T4 condition than that of O condition. The hardness in T4 temper is higher due to the presence of more number of strengthening precipitates which were observed from the SEM micrographs in electron beam welding, slightly higher hardness values are recorded in O condition than that of PWHT condition. This is attributed to the reduced width of PMZ in PWHT condition.

| BM    | O   | T4  |
|-------|-----|-----|
| AA2014| 126 | 154 |

**Table 3 Vickers hardness values of base metals in O and T4 conditions**

| Weld Zone | FZ       | PMZ      | HAZ      |
|-----------|----------|----------|----------|
| O         | 92-97    | 95-104   | 105-111  |
| PWHT      | 64-70    | 90-95    | 87-106   |

**Table 4 Vickers hardness values of AA2014EB welds in O and PWHT conditions**
3.3 Pitting corrosion studies

The role of alloying elements was to mainly change the local corrosion potentials on the surface of the alloy. Intermetallic particles and the equilibrium precipitates in the microstructure of base metal weaken the passive film and are the sites for pit nucleation. Cathodic intermetallics produce a galvanic cell with aluminium matrix and act as cathode for oxygen reduction. The potentiodynamic polarization [Epit] values of base metal AA2014 and various zones in AA2014 EB welds in O and PWHT conditions are given in Tables 4 and 5. Potentiodynamic polarization curves of base metal AA2014 in O and T4 conditions are shown in Fig. 7. The pitting corrosion resistance of base metal in T4 condition is better than that of O condition. This is attributed to the evenly distributed discontinuous finer eutectics present in T4 condition. The pitting corrosion resistance of AA2014 alloy in O condition was poor. It may be attributed to the large number of copper rich intermetallics [CuAl2] and equilibrium precipitates present as is evident from optical microstructures. Very early establishment of the local action cells of corrosion between the precipitates and Al-matrix decreases the pitting resistance of the alloy. Results of the potentiodynamic polarization tests on AA2014 alloy are given in the Table 5. It is very clear from this data that pitting corrosion resistance of the base metal in soft condition is poor when compared to that of T4 condition. This could be attributed to the formation of coherent precipitates in T4 condition which may not form the galvanic cell during corrosion. From Table 6, the values indicated that the pitting corrosion resistance of the PMZ/HAZ in PWHT condition is better than that of O condition. This is attributed to copper segregation at the grain boundaries of PMZ in O condition, which is evident from SEM-EDX values of AA2014 EB welds in O and PWHT conditions [Table 7]. The fusion zone exhibited higher positive Epit values than PMZ/HAZ. This is attributed to lower copper enrichment at the dendritic boundaries when compared to that of PMZ. The potentiodynamic polarization curves of PMZ/HAZ of AA2014 EB welds in O and PWHT conditions are shown in Fig. 8. These curves also confirmed that the welds possess good corrosion resistance in PWHT condition than that of O condition.

| Condition | Epit (mV), SCE of AA2014 alloy in O and T4 conditions |
|-----------|--------------------------------------------------|
| O         | -633                                             |
| T4        | -600                                             |

| Weld Zone | Condition | FZ   | PMZ/HAZ |
|-----------|-----------|------|---------|
| O         |           | -621 | -656    |
| PWHT      |           | -589 | -603    |

| Position | Mg  | Al  | Cu  |
|----------|-----|-----|-----|
| GB       | 2.98| 65.2| 27.94|
| GB       | 1.61| 72.61| 11.73|
Fig. 7 Potentiodynamic polarization curves of base metal AA2014 in O and T4 conditions

Fig. 8 Potentio-dynamic polarization curves of PMZ/HAZ in AA2014 EB welds in O and PWHT condition

Formation of pits was evident from the optical micrographs as shown in Fig. 9 of the potentio-dynamic polarized AA2014 alloy in O and T4 condition. Pits were found to be regular in shape with uniform distribution in T4 condition than in O condition. The optical micrographs of post corrosion samples in PMZ/HAZ in O and PWHT conditions are shown in Fig. 10. From the micrographs, it is noticed that the pit density in PMZ/HAZ of the welds is more in O condition than that of PWHT condition. This is the evidence for better corrosion resistance of welds in PWHT condition than that of O condition.
4. Conclusions

1. The microstructures show white matrix of α-solid solution grains and the second phase particles appearing as black in color. Quite large particles (2-10μm) were present both within grains and at grain boundaries.

2. The microstructure of fusion zone in O condition consists of fine grains of CuAl$_2$ eutectics appearing in the dendritic matrix of α-solid solution. The eutectics are present within the grains and along the grain boundaries. Whereas the thickness of the grain boundary eutectics was reduced after PWHT and the grains were coarsened.

3. Weld in O condition is prone to more liquation than that of PWHT condition. This may be attributed to re-melting and solidification of excess eutectic present in the O condition of the base metal. Slightly higher hardness values are recorded in O condition than that of PWHT condition.
4. The pitting corrosion resistance of the PMZ/HAZ in PWHT condition is better than that of O condition. This is attributed to copper segregation at the grain boundaries of PMZ in O condition. The fusion zone exhibited higher positive Epit values than PMZ/HAZ. This is attributed to lower copper enrichment at the dendritic boundaries when compared to that of PMZ.

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