Research Article

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Influence of post weld heat treatment on tensile properties of cold metal transfer (CMT) arc welded AA6061-T6 aluminium alloy joints

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Abstract: Aluminium alloys of 6xxx series are widely used in the fabrication of light weight structures especially, where high strength to weight ratio and excellent weldability characteristics are desirable. Gas metal arc welding (GMAW) is the most predominantly used welding process in many industries due to the ease of automation. In this investigation, an attempt has been made to identify the best variant of GMAW process to overcome the problems like alloy segregation, precipitate dissolution and heat affected zone (HAZ) softening. Thin sheets of AA6061-T6 alloy were welded by cold metal transfer (CMT) and Pulsed CMT (PCMT). Among the two joints, the joint made by PCMT technique exhibited superior tensile properties due to the mechanical stirring action in the weld pool caused by forward and rearward movement of the wire along with the controllable diffusion rate at the interface caused by shorter solidification time. However, softening still exists in the welded joints. Further to increase the joint efficiency and to minimize HAZ softening, the joints were subjected to post weld heat treatment (PWHT). Approximately 10% improvement in the tensile properties had been observed in the PWHT joints due to the nucleation of strengthening precipitates in the weld metal and HAZ.

Keywords: Aluminium alloys, Cold metal transfer, Pulsed cold metal transfer, Post weld heat treatment, Tensile properties, Microstructure

1 Introduction

The fabrication of the light weight structures demands the necessity of aluminium alloys in the automobile sector. Many designers and technologists are facing lot of challenges in welding of aluminium alloys by the conventional welding processes. This is due to the presence of persistent oxide layer, high thermal conductivity and coefficient of thermal expansion. Welding of heat treatable aluminium alloys by conventional fusion welding processes are limited in usage in the industrial applications due to the dissolution or coarsening of strengthening precipitates caused by the excess heat input [1]. In particular, the heat treatable aluminium alloys are of significant importance in the hood, trunk and door applications. The conventional gas metal arc welding (GMAW) process is limited in the industrial sector due to the problems such as wider heat affected zone (HAZ) with higher degree of softening with respect to the base material [2]. The hardness degradation region in the HAZ and weld metal zone (WMZ) of aluminium alloy joints is the major issue in conventional GMAW process and this issue deteriorates the tensile properties of the welded joints enormously. In order to overcome the above mentioned problem, a low heat input welding process is preferable and hence the low heat input GMAW variants like cold metal transfer (CMT) and pulsed cold metal transfer (PCMT) could be used to weld thin sheets of aluminium alloys [3].

CMT arc welding process is characterized by the short circuiting metal transfer where the droplet detachment is aided by the backward movement of the electrode. This backward movement of the electrode takes place only when the droplet touches the weld pool that results in lowering of the current during short circuiting. The transfer of droplets in CMT welding process takes place without
fractionating the liquid bridge unlike the conventional GMAW process. This specifies that CMT welding process not only reduces heat input but also produces spatter free welds [4–6].

Hakan Aydın et al. [7] stated that conventional welding processes led to a significant reduction in mechanical properties of the aluminium alloy welded joints since the alloy underwent phase transformation and softening in the HAZ. Kah et al. [8] reviewed the advanced variants of GMAW and concluded that the main reason for the advancement in the GMAW process is to overcome the weld defects, increase process efficiency and joint strength by reducing the heat input. This leads to the reduction in the spatter and increase the flexibility of the welding machine. Jie Pang et al. [9] studied the arc characteristics and metal transfer behavior of PCMT process and observed that stable and spatter free metal transfer was attained with the PCMT process. They confirmed that the higher initial arc current and low current as well as the current pulsing during the pulse period controlled by the waveform synergic program leads to a stable metal transfer. Pavan Kumar et al. [10] studied the CMT welding process parametric effects on the microstructural aspects of AA6061 aluminium alloy joints and found that stable and spatter free welds were obtained with the CMT welding process.

Maisonnette et al. [11] reported that the mechanical properties of the HAZ were deteriorated due to the dissolution or coarsening of precipitates. They observed that fine β'' precipitates with a mean diameter of 4.45 nm and volume fraction of about 1.6% in the microstructure by employing the post weld heat treatment. This resulted in the improvement in mechanical properties. Javier Serrano Perez et al. [12] observed that by employing post weld heat treatment (PWHT) for the gas metal arc welded aluminium alloy joints, the softening gets reduced drastically in the weld metal zone and opined that it was due to the generation of Mg and Si elements caused during the artificial aging treatment that facilitates the formation of β'' precipitates. They concluded that there is a drastic improvement in the mechanical properties of the GMA welded aluminium alloy joints due to the PWHT. Gaofeng Fu et al. [13] suggested that artificial aging (AA) treatment is preferable compared with the natural aging (NA) in restoring the mechanical properties that are degraded in the welded condition. They observed that softening in the HAZ was eliminated by employing the PWHT which was confirmed by the hardness survey.

Research work done to control the precipitate coarsening or dissolution of hardening precipitates in the HAZ of aluminium alloy joints is very scant. This has drawn the attention of many researchers to control this issue by incorporating the low heat input welding processes such as CMT and PCMT. However, softening still exists in the welded joints. This stimulated to carry out this research work to study the effect of PWHT on tensile properties of cold metal transfer arc welded AA6061-T6 aluminium alloy joints.

### 2 Experimental work

AA6061-T6 aluminium alloy sheets of 3 mm thickness were chosen as base material and single V butt joint configuration was prepared with an included groove angle of 60°. The filler wire selected was ER4043 of 1.2 mm diameter. The chemical composition and mechanical properties of the base metal and filler metal are presented in Table 1 and 2 respectively. Two variants of GMAW process were employed to weld aluminium alloy sheets using the welding machine as shown in Figure 1. They were i) cold metal transferred (CMT) ii) pulsed CMT (PCMT). The welding parameters chosen for welding these sheets are presented in Table 3. In addition to the process parameters mentioned in the Table 3, the pulsing parameters such as peak current
Table 3: Optimized welding parameters used to fabricate the joints

| Variant | Welding current (A) | Arc voltage (V) | Arc length correction (%) | Wire feed speed (mm/min) | Pulse Frequency (Hz) | Welding speed (mm/min) | Heat input (kJ/mm) |
|---------|---------------------|-----------------|---------------------------|--------------------------|----------------------|------------------------|-------------------|
| CMT     | 116                 | 14              | 15                        | 5600                     | -                    | 480                    | 0.177             |
| PCMT    | 111                 | 13.2            | 15                        | 5000                     | 292                  | 480                    | 0.164             |

(Note: PCMT: I_p = 82.2 A, t_p = 2.43 ms, I_b = 280 A, t_b = 1 ms)

The cross section of the microstructural specimens were initially polished with a diamond paste and then etched using Keller’s reagent to reveal the microstructure.

The hardness variation across the welded joint was measured using Vicker’s micro hardness tester with a load of 100 gms and dwell time of 15 seconds. Transverse tensile properties were evaluated by performing the tensile test on the electro mechanically controlled universal testing machine. Optical microscopy was used for characterizing the metallography specimens. Scanning electron microscopy (SEM) with energy dispersive X-ray spectroscopy (EDS) analysis was done along the grain boundary region...
Table 4: Transverse tensile properties of base metal and welded joints

| Joint condition | 0.2% Yield strength (MPa) | Ultimate Tensile strength (MPa) | Elongation in 50 mm gauge length (%) | Notch tensile strength (MPa) | Notch strength ratio | Joint efficiency (%) | Fracture location |
|-----------------|---------------------------|---------------------------------|--------------------------------------|----------------------------|---------------------|----------------------|-------------------|
| BM              | -                         | 275 (1.98)                      | 318 (2.02)                           | 16 (0.02)                  | 325                 | 1.02                 | -                 |
| CMT AW          | 190 (4.74)                | 215 (5.14)                      | 9.02 (0.08)                          | 220 (4.06)                 | 1.02                | 67.6                 | HAZ               |
| PCMT AW         | 197 (3.15)                | 227 (4.26)                      | 9.15 (0.05)                          | 234 (5.04)                 | 1.03                | 71.3                 | HAZ               |
| CMT PWHT        | 197 (3.24)                | 227 (3.53)                      | 9.15 (0.05)                          | 247 (4.22)                 | 1.02                | 76.1                 | HAZ               |
| PCMT PWHT       | 220 (4.05)                | 250 (4.22)                      | 9.62 (0.09)                          | 257 (4.68)                 | 1.028               | 78.6                 | HAZ               |

Note: The values mentioned in the bracket are standard deviation

3 Results

3.1 Tensile properties

The transverse tensile properties of the welded joints presented in Table 4 are the average of three tensile test specimens. The fracture location of the smooth tensile specimens before and after test is shown in the Figure 5. Stress strain curves of the AW and PWHT welded joints are shown in Figure 6. In the as welded condition, PCMT joint shows the highest tensile strength of 227 MPa with an elongation of 9.15% among the two welded joints. However, the post weld heat treated PCMT joint records an improved tensile strength of 250 MPa which is 10% higher than the AW joint.

Notch Strength Ratio (NSR)

\[
\text{NSR} = \frac{\text{Tensile strength of the notched specimens}}{\text{Tensile strength of the unnotched specimens}}
\]

Joint Efficiency (\(\eta\))

\[
\eta = \frac{\text{Tenisle strength of the joint}}{\text{Tenisle strength of the base metal}}
\]

All the joints regardless of the process variants and post weld heat treatment recorded a notch strength ratio (NSR) greater than one. This suggests that all the weld metal falls under the notch ductile category. The joint efficiency of the post weld heat treated CMT and PCMT joints are 76.1 and 78.6% respectively which is 10 and 12.5% higher than the as welded CMT and PCMT joints. Hence there is an appreciable improvement in the tensile properties of the PWHT joints was observed.
Table 5: EDS results (wt%) of the weld metal regions in the welded joints from Figure 12

| Joint condition | Al    | Mg    | Si    | Mn    | Ti    |
|-----------------|-------|-------|-------|-------|-------|
| CMT AW          | 95.86 | 1.40  | 2.68  | 0.04  | 0.02  |
| PWHT            | 94.67 | 1.64  | 3.57  | 0.07  | 0.01  |
| PCMT AW         | 95.74 | 1.29  | 2.95  | 0.02  | 0.01  |
| PWHT            | 94.44 | 1.85  | 3.66  | 0.04  | 0.01  |

Figure 7: Microhardness distribution of the welded joints

3.2 Microhardness

Figure 7 illustrates the microhardness distribution profile of the AW and PWHT joints. It shows that the low hardness is recorded in the HAZ and the highest hardness is recorded in the WM region irrespective of the welding techniques. The low hardness in the HAZ region confirms the possibility of softening since the hardness recorded is 50% lower than the base material [14]. The higher hardness in the WM region is due to the enrichment of the solid solution with Mg and Si eutectic phases. This enrichment phenomena happens mainly because of the dissolution process [15]. PCMT joint records a higher hardness of 79 HV in the weld metal zone which is 6.7% higher than the CMT joint in the as welded condition. Whereas in the PWHT condition, an increase in the hardness in the WM zone is observed i.e., 14% improvement in CMT joint and 12% improvement in PCMT joint. Moreover the degree of softening in the HAZ is deduced in all the joints due to PWHT condition.

3.3 Microstructure

Equiaxed and elongated grains are observed in the base metal microstructure. The microstructures of the WM, WM-HAZ interface and the HAZ region of all the four joints under AW and PWHT condition are shown in Figures 8, 9 & 10 respectively. Due to the weld thermal cycles, coarser grains exists in the HAZ region, equiaxed to columnar grains are present at the interface of the joints, and columnar dendritic grains are observed in the weld metal irrespective of the welding techniques employed. The variation of the grain size in various zones based on the weld thermal cycle is almost similar in both the cases i.e., AW and PWHT condition as suggested by Elangovan et al. [16].

XRD analysis was done in the weld metal region of all the joints (AW and PWHT) and the results are presented in Figure 11. The phases that are formed in the CMT and PCMT joints are Al, Mg$_2$Si, Al$_8$Fe$_2$Si and FeSi$_2$. Therefore it is identified that the phases formed in CMT and PCMT joints are similar but their intensity level reduces in case of PCMT joints. It was also noticed that the phases formed in the PWHT condition are similar to the AW condition, but their level of intensity reduces as pointed out by Hao et al. [17]. Therefore it is concluded that the segregation of phases can be controlled significantly by adopting the PWHT. This can be confirmed by the EDS spectrum analysis. EDS analysis was done along the grain boundary of the WM region (Figure 12) and the results are presented in the Table 5. It is found that the segregation of elements is less in the PCMT joints compared with the CMT joints and it was due to the low temperature and faster cooling rate in the PCMT joint helps in controlling the formation of segregated phases.
Figure 8: Optical micrographs of the WM zone of joints in AW and PWHT condition

Figure 9: Optical micrographs of the interface region of joints in AW and PWHT condition
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|       | AW Joint        | PWHT Joint       |
|-------|-----------------|------------------|
| CMT   | ![Micrograph](image1.png) | ![Micrograph](image2.png) |
| PCMT  | ![Micrograph](image3.png) | ![Micrograph](image4.png) |

**Figure 10:** Optical micrographs of the HAZ region of joints in AW and PWHT condition

|       | AW Joint       | PWHT Joint       |
|-------|----------------|------------------|
| CMT   | ![XRD](image5.png) | ![XRD](image6.png) |
| PCMT  | ![XRD](image7.png) | ![XRD](image8.png) |

**Figure 11:** XRD analysis of the joints in both AW and PWHT condition
| Variants | AW Joint | PWHT Joint |
|----------|----------|------------|
| CMT      | ![CMT AW Joint](image1) | ![CMT PWHT Joint](image2) |
| PCMT     | ![PCMT AW Joint](image3) | ![PCMT PWHT Joint](image4) |

**Figure 12:** EDS analysis of the segregated phases in the WM region

**Figure 13:** SEM fractographs of the smooth tensile specimens
3.4 Fracture surface

The fracture location is a direct indication of the weakest point in the joint. The fractographs of the smooth tensile specimens are shown in Figure 13 and the notch tensile specimens are shown in Figure 14. The dimples are formed in an uniform manner on the fracture surface of the smooth tensile specimens. Therefore the mode of failure in all the smooth tensile specimens is ductile mode irrespective of the heat treatment condition. Where the fracture surface of notch tensile specimens are characterized by both cleavage and dimples. Hence the mode of failure of the notch tensile specimens happens in a quasi-cleavage mode regardless of the heat treatment condition.

4 Discussion

In general, CMT welding process does not need high current to fracture the liquid bridge. There are two stages in the pulsed CMT process i.e., arcing phase and short circuiting phase. The arcing phase consists of pulse period and base period. Due to the peak current in the pulse period, a molten droplet is expected to form at the tip of the electrode and the current comes down during the base period. During the short circuiting phase, the current gets down further and finally the metal transfer takes place smoothly by the retracting movement of the electrode. The cyclic process continues and followed by the reignition of the arc. The melting of the electrode takes place once the ignition of the arc enters the peak phase in a pulse period. Then during the base phase in pulse period, the current is lowered and therefore the intensity of the arc gets reduced without allowing the droplet to detach. After the occurrence of numerous pulses, base period exists in which the electrode moved towards the weld pool and once the electrode touches the weld pool the arc gets extinguished. The molten droplet gets detached from the electrode tip only with the backward movement of the electrode. Therefore stable and spatter free metal transfer could be attained during this process. The cycle repeats by the reignition of the arc.

Therefore in CMT and PCMT processes, due to the low temperature gradient and formation of heterogeneous nuclei, the segregation of eutectic elements are controlled drastically. Hence it is noted that segregation of elements can be controlled significantly because of the low heat input involved in the CMT and PCMT process. Segregation of alloying elements such as Mg forms along the grain boundary in the WM zone is observed on welding of alu-
minium alloys because of the coherency of precipitates with the aluminium matrix [18]. The variation of hardness values across the cross section of the welded joints is due to the density distribution of precipitates. Higher hardness is recorded in the WM zone compared with the HAZ due to the enrichment of solid solution with eutectic elements like Mg and Si while the lower hardness is observed in the HAZ due to the dissolution or coarsening of the precipitates in the HAZ [19]. This results in the formation of softening in the HAZ. This higher hardness in the WM zone and lower hardness in the HAZ is observed regardless of the process used.

Heat treatment is the essential process that helps in regeneration of nuclei (i.e., the formation of precipitates) in the matrix. The heat treatment procedure employed in this investigation is solutionizing followed by quenching and then artificial aging. During solutionizing, the solid solution is enriched with supersaturated vacancies and solute atoms while during the quenching process, it makes the atoms to enter into supersaturation state. Finally on artificial aging, the precipitates gets nucleated by the supersaturation of solute atoms and higher concentration of vacancies [20]. Hardness improvement is observed in the PWHT joints irrespective of the welding process. Therefore it is inferred from the microhardness distribution, that soft zone is eliminated in the HAZ irrespective of the process by performing the PWHT on the welded joints.

PWHT helps in restoring the alloying elements that are dissolved during welding and ultimately makes the joints in recovering the strength but the ductility is reduced. Enhancement in the tensile strength is observed due to the increasing density distribution of the hardened precipitates [21]. Also the ductility is improved in both the CMT and PCMT joints because of the limited flow stress. Improved strength in the CMT and PCMT joints is observed due to the high concentration of the vacancies and supersaturation of the solute atoms that enhances the movement of \(\beta''\) precipitates during the artificial aging. The resistance to nucleation of precipitates is less in case of CMT and PCMT joints because of the faster cooling rate [22]. This generation of \(\beta''\) precipitates attributes to the hardening of the WM zone in these joints.

In CMT process, the stronger electromagnetic force attributes constitutional super cooling effect which helps in controlling the segregation of phases to some extent. Whereas in PCMT process, the pulsing effect in the peak phase helps to reduce the level of segregation of phases tremendously. The narrow soft zone and HAZ region in the PCMT joint along with controlled segregation of phases is attributed to the superior tensile properties due to the combined effect of pulsing and dip and with drawl movement of the wire in PCMT process. However softening still persists in the HAZ region of the welded joints. Therefore in order to increase the joint efficiency and minimize the HAZ softening, PWHT is employed. In PWHT joints, the intensity level is still reduced to a lower value, which is evident from the XRD graphs irrespective of the welding process. This is one of the reasons for the improvement in the tensile properties of the welded joints immensely.

5 Conclusions

(i) The joints made by PCMT (Pulsed cold metal transfer) process exhibited superior mechanical properties than CMT process. This is due to the low temperature gradient and more heterogeneous nuclei caused by the forward and backward movement of the filler wire associated with the current pulsing effect that helps in controlling the segregation of phases.

(ii) HAZ softening has been resolved drastically in all the joints by adopting the PWHT procedure regardless of the welding technique. This is due to the formation of hardening precipitates in the joint during the artificial aging process. It is observed that the hardness values in the HAZ of the post weld heat treated PCMT joint is 78 Hv which is nearer to the WM zone hardness.

(iii) Post weld heat treated PCMT joint recorded the highest tensile strength of 250 MPa which is 16% higher than the as welded CMT joint, 10% higher than aswelded PCMT joint and 5% higher than PWHT-CMT joint. This is because of the nucleation of hardened \(\beta''\) precipitates in the matrix during PWHT.

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