Effect of post-weld heat treatment on tensile strength and microstructure characteristics in dissimilar friction welded (AA6061–AA7075-T6) joints

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Abstract
Dissimilar AA6061 to AA7075-T6 joints fabricated by friction welding has been investigated to enhance the mechanical properties by post-weld heat treatment (PWHT) process. After fabrication, the welded samples are heat-treated by three different conditions namely, solution treatment, artificial aging and solution treatment followed by aging. Following this, the tensile properties and microhardness of PWHT specimens were systematically investigated. Further, the influence of PWHT in fully deformed zone, partially deformed zone, heat affected zone, and parent metals were examined through the optical microscopy, scanning electron microscopy, transmission electron microscopy and energy dispersive spectrum. Finally, the results of PWHT specimens were discussed and compared with as-welded conditions.

1. Introduction

Both the AA6061 and AA7075 aluminum alloys are heat treatable (age hardenable), most widely used in automation, shipyard and aerospace industries. The AA6061 is commercially used to manufacture the vehicle wheels, side panels and frames. On the other hand, the 7075 Al-alloys for its excellent low weight and high strength proportion are in demand for aerospace applications [1, 2]. The problems incurred during fusion welding of aluminum alloys were eliminated by solid state welding like friction welding [3]. FW process is an eco friendly welding process in which the joint can be fabricated faster than that of any other welding process. The FW process attracted the attention of the researchers because of its simplicity and easy handling. Especially for joining the dissimilar materials in rod form, FW process is most suitable [4, 5]. Usually the age hardening alloys undergo precipitation dissolution when it reaches the solid solution temperature. Fully deformed zone (FDZ) and partially deformed zone (PDZ) of the friction welded AA 6061 experiences the solutionising temperature due to generation of excessive frictional heat [6]. Hence semi coherent (finer) precipitates disappear in the welded zones so that, the joint efficiency is lowered. To strengthen the welded specimen, the post weld solid solution treatment is the primary step to impart the semi coherent precipitates.

Balasubramanian et al investigated that the PWHT deeply altered the microstructure of the specimen in the welded region [7]. Jamshidi aval Hamed, studied the effect of aging on tensile properties of dissimilar (AA7075 – AA5086) joint fabricated by FSW process and reported that, the grain size in the weld zone towards AA5086 side was found to be coarser than AA7075 side [8]. Priya et al, reported the failure location was changed from the heat affected zone (HAZ) of AA6061 side to the fusion zone due to effect of solution treatment and aging [9]. Hossein Karami Pabandia et al, reported the fine precipitates particle of Mg2Si was distributed uniformly in the solution treated weld zone of the dissimilar alloys (AA2024-T6 and AA6061-T6) which resulted in significant improvement of tensile strength [10]. PWHT effects on various aspects of mechanical properties of different grades of aluminum alloys like AA2024, AA6063, AA6082 and AA7075 were previously investigated.
The effects of PWHT on mechanical properties of various dissimilar combinations also studied [18–24]. However no work has reported the comprehensive details for the effects of PWHT on mechanical properties for the specific combination of friction welded dissimilar AA6061 and AA7075-T6 alloys.

2. Experimental procedure

2.1. Materials, friction welding and heat treatment

In this study, the age hardenable alloys like AA6061 and AA7075-T6 have been used as parent metals. Specimen used for investigation has 12 mm diameter and 75 mm length. Table 1 shows the chemical composition and table 2 shows the FW process parameters used for manufacture the joints. A set of FW parameters which produces the maximum strength of the joint using design of experiment has been chosen for this investigation [1]. Dissimilar joints are fabricated by using hydraulic controlled continuous driving friction welding machine. During the FW process, AA6061 was fixed in the moving side and AA7075-T6 was fixed in the rotating side of the FW machine. To strengthen the fabricated specimens, three post weld heat treatments namely solution treatment, solution treated followed by aging (STA) and artificial aging (AA) are performed. The induction furnace was used to heat treat the specimens from the room temperature to required temperature as per the ASM handbook standard. Solution treatment (ST) was done at 500 °C and the rate of heating is 100 °C/min with 60 min soaking time. Then the ST specimens were taken out from the furnace and quenched in cold water. To study the combined effect of solution treatment and aging, the solution-treated samples were placed in the furnace at 160 °C at same rate (100 °C/min) for 8 h soaking duration to carry out artificial aging. It is being kept in the furnace until it reaches the room temperature. The artificial aging alone carried out to 160 °C at the temperature rate of 100 °C/min with 8 h soaking time. The purpose of separate AA is to compare the responses with ST, STA and as welded conditions.

2.2. Mechanical and metallurgical study methods

After the heat treatment, all the specimens (AW, ST, AA and STA) are sized (notched and smooth specimens) as per the ASTM E8 standard for tensile tests and it was carried out on an automated hydraulic universal testing machine with 120 kN capacity. After the tensile test, the morphology of the fractured specimen surfaces was studied by using scanning electron microscope (SEM). Micro hardness study was done across the cross section of the joints by using Vicker’s hardness method under 0.5 N load and 10 s dwell time. The standard metallographic method was adopted to prepare specimens for microstructure examination. The ASTM E407 guidelines were followed to etch the specimens and it is done with a concentric Keller’s etchant and then digital optical microscope was employed to carry out the microstructure examination. Finally transmission electron microscopy (TEM) observation and energy dispersive spectrum (EDS) analysis were performed to evaluate precipitates formation on the specimens across the weld regions.

3. Results

3.1. Tensile properties

The stress-strain relationship curve for as welded (AW) and PWHT joints shown in figure 1 and the results obtained from the tensile test are presented in table 3. AW condition of the specimen recorded the lower strength

| Alloy  | Ti   | Si   | Mn   | Cr   | Fe   | Cu   | Mg   | Zn   | Al   |
|-------|------|------|------|------|------|------|------|------|------|
| AA6061 | 0.019 | 0.506 | 0.068 | 0.214 | 0.219 | 0.248 | 0.921 | 0.008 | Bal. |
| AA7075-T6 | 0.065 | 0.088 | 0.108 | 0.235 | 0.603 | 1.638 | 2.221 | 5.456 | Bal. |

Table 2. FW process parameters.

| FW parameters | Values |
|---------------|--------|
| Rotational Speed (rpm) | 1200 |
| Friction Pressure (MPa) | 35 |
| Forging Pressure (MPa) | 35 |
| Friction time (sec) | 3 |
| Forging time (sec) | 3 |
compared to parent metals, STA and AA joints. It exhibits the joint efficiency of 73% compared with AA6061 parent metal and 39% with AA7075-T6. The STA conditioned specimen produced the highest strength of 292 MPa among the all treated specimens and the strength is 96% compared to AA6061 base metal and 52% compared to AA7075-T6. Artificial aged joint recorded the second highest of tensile strength of 256 MPa and ST joint exhibits the lower strength of 204 MPa among the all.

The notch strength ratio \((NSR)\) of the as welded samples is found to be 0.97 which is higher than the ST, STA and AA. However the NSR values for the other three conditions are almost similar. The percentage of elongation observed in ST condition is 11.8% which is high compared to STA and AA. Overall properties recorded in STA samples expect elongation higher than the AA6061 parent metal, AW, ST, and AA and lower than 7075 T-6. Moreover the maximum strain rate of 13% (except parent metals) was recorded in AW joints and lower rate of 8.1% was observed in AA joints. Solution treated joint fractured at HAZ region AA6061 side and all other (AW, STA and AA) joints were fractured very nearer to weld zone towards AA6061, which is referred as partially deformed zone.

3.2. Fractured surfaces

The fractured surface captured by SEM for the parent metals (PM), AW, ST, STA and AA joints are shown in figures 2(a)–(f). A large number of finer dimples formed along the loading direction were seen in (figures 2(a) and (b)) both base metals and more number of micro voids in different sizes are observed around these fine dimples. Moreover the crack is initiated at the micro voids during mechanical loading in tensile test. On the other hand, less number of micro voids and dimples were seen in (figure 2(c)) AW joint and the fracture surface of the ST joint shows (figure 2(d)) the coarse and elongated dimples in larger number when compared to AW joint. Figure 2(e) shows the AA joint fracture surface characterized with large number of dimples and bottomless micro voids compared to ST and AW joints. The fracture surface of the STA joint (figure 2(f)) shows the extensive presence of fine populated dimples and these dimples are much shallower compared to all others joints. The quantitative results of fracture surfaces using image analyzing software are listed in the table 4.

Further the results reveal that, all the joints may not have significant differences with respect to the variation in dimple size. Contrary, the percentage of distribution of dimples shows the significant variations irrespective of dimple size. The average dimple size measured in AW and STA joints are almost similar but the STA joint recorded the highest (74%) dimples distribution in the fracture surface when compared to AW, ST and AA joints. On the other hand, AW joint recorded the lowest percentage (53%) of dimple distribution with respect to all the joints. Over all in fractured morphology, the micro voids associated with fine \((\theta)\) precipitate particles (STA joint) and larger voids associated with coarser \((\theta)\) precipitate particles (ST joint and AA joint) during tensile testing.

3.3. Micro hardness

Figure 3 depicts the micro hardness measured across the welded specimens at various regions of joints for all treated conditions. The hardness observed in FDZ of the AW specimen exhibits the lower hardness value (139 HV) compared to STA and AA joints. Further the hardness recorded (125 HV) in HAZ of AA7075-T6 side was lower than FDZ. The solution treated joint exhibits lower hardness profile compared to all other joints and the measured hardness in the FDZ was 116 Hv. Artificially aged joints record the second highest hardness value of
Table 3. Tensile properties of parent metals and FW joints.

| Joint       | Yield strength (MPa) | Tensile strength (MPa) | Notch tensile strength (MPa) | Notch strength ratio (NSR) | Elongation in mm | Fracture location         |
|------------|---------------------|------------------------|-----------------------------|---------------------------|------------------|---------------------------|
| AA 6061 (PM) | 272                 | 304                    | 328                         | 1.07                      | 19.3             | —                         |
| AA7075-T6 (PM) | 512                 | 569                    | 583                         | 1.02                      | 13.2             | —                         |
| AW         | 185                 | 228                    | 216                         | 0.97                      | 13               | PDZ of AA6061 side        |
| ST         | 176                 | 204                    | 180                         | 0.88                      | 11.8             | HAZ of AA6061 side        |
| AA         | 212                 | 256                    | 222                         | 0.87                      | 8.1              | PDZ of AA6061 side        |
| STA        | 238                 | 292                    | 246                         | 0.84                      | 9.8              | PDZ of AA6061 side        |
153 HV in FDZ and no difference were observed between the FDZ, PDZ and HAZ in the AA7075 T6 side. Solution treated followed by artificial aging specimen shows a significant improvement in hardness in all the zones compared to AW, ST and AA. The highest hardness value of 182 HV recorded in the parent metal of 7075-T6 side in STA joint which was higher than both base metals. Hardness of 164 HV was observed in weld region.

**Figure 2.** SEM fracture surfaces (a) AA6061-PM, (b) AA7075 PM, (c) AW joint, (d) ST joint, (e) AA joint, (f) STA joint.

**Table 4.** Image analysis results of fracture surface.

| Joint       | Size of dimples (µm) | Average size | Area percentage of distribution of dimples |
|-------------|----------------------|--------------|-------------------------------------------|
| AA6061 (PM) | 2.8 to 10.2          | 6.24         | 75                                        |
| AA7075-T6 (PM) | 3 to 12            | 7.06         | 80                                        |
| AW          | 2 to 9              | 5.34         | 53                                        |
| ST          | 3.4 to 11           | 6.73         | 68                                        |
| AA          | 3.8 to 11.2         | 7.8          | 71                                        |
| STA         | 3.1 to 12.6         | 5.50         | 74                                        |

153 HV in FDZ and no difference were observed between the FDZ, PDZ and HAZ in the AA7075 T6 side. Solution treated followed by artificial aging specimen shows a significant improvement in hardness in all the zones compared to AW, ST and AA. The highest hardness value of 182 HV recorded in the parent metal of 7075-T6 side in STA joint which was higher than both base metals. Hardness of 164 HV was observed in weld region.
(FDZ) of the STA condition which is 1.18 times higher than the AW conditions. STA and AA joints shows the marginal improvement in hardness on AA6061 side compared to AW and ST joints. The partially deformed zone in the AA6061 side shows rapid variation in hardness from PDZ towards FDZ in all conditions whereas in 7075-T6 side no such kind of fluctuation was observed.

3.4. Microstructure

The optical micrograph revealing grain structure for the conditions such as parent metals (PM) and weld region of AW, ST, STA and AA joints are shown in figures 4(a)–(e). The co-axial grain structure was observed in AA 6061 (figure 4(a)) and AA7075–T6 has (figure 4(b)) longitudinally oriented grains. In AA 7075–T6, the formation of elongated grains viewed towards the rolling/forming direction.

The fully deformed zone of AW and ST joints (figures 4(c) and (d)) shows the dynamically recrystallized structure with finer grains compared to parent metals and no significant level of grains growth is observed in (figures 4(e) and (f)) the weld region of STA and AA joints. However the grains size noticed in the STA and AA joints is a bit higher than that of AW joints.

Figures 5(a)–(h) shows the grain structure of the partially deformed zone (PDZ) of all the specimens in either side (AA6061 and AA7075–T6). The microstructure of PDZ in both AA6061 and 7075–T6 sides shows the progress of grain range towards the FDZ.

The PDZ region on AA6061 side reveals the rapid changes in the grain size and setup towards the weld region. Further the marginal improvement in grain size was observed (figures 5(e) and (g)) in the AA6061 side of AA and STA joints. On the contrary, in PDZ of 7075–T6 region the coarsened grains are towards fusion zone. Moreover no considerable changes were seen in (figures 5(b) and 6(d)) AA 7075–T6 side in the AW and ST joints, but some finer precipitates are randomly distributed in AA and STA joints (figures 5(f) and 6(h)).

The TEM micrograph revealing precipitates details for the conditions such as parent metals (AA6061 & AA7075 T6) and weld region of AW, ST, STA and AA are shown in figures 6(a)–(f). The crucial precipitate in 6xxx (Al–Mg–Si–Cu) alloy series is Mg2Si [25, 26]. Similarly, the crucial precipitates in 7xxx (Al–Zn–Mg–Cu) alloy series are MgAl2, CuAl2 and Al2CuFe [27]. The effective heat treatment of the welded joints will configure and distribute these precipitates. In both the parent metals, two types of precipitates are observed through the TEM macrograph figures 6(a), (b).

The AA6061 base metal associated with globular precipitates which are clearly seen in figure 6(a). The coarse (θ) precipitates size estimated from 50 nm to 133 nm and finer (θ') precipitates size vary from 28 nm to 50 nm. On the other side 7075 T–6 base metal (figure 6(b)) characterized with large number of normally oriented needle precipitates. The size of coarse particles varied from 50 nm to 102 nm and fine precipitates of size vary from 16 nm to 50 nm. In as welded joint, the finer precipitates in the FDZ entirely dissolved in the aluminum region due to the generation of frictional heat during the FW process.

No precipitate is to be seen (figure 6(d)) in the FDZ of ST joint and some cleavage also seems to be observed. The coarse precipitates of Al2CuFe which is block and spherical in morphology measures the size 148 of nm (figure 6(e)) was seen in the AA joint. The significant level of finer particles of size varied from 10 nm to 50 nm also observed (figure 6(e)) in the FDZ of AA joint. On the contrary, in STA joint (figure 6(f)) the agglomerated

![Figure 3. Microhardness of the AW, ST, AA and STA joints.](image-url)
precipitates completely dissolve in the aluminium matrix and finer particles (from 6 nm to 38 nm) seem to be evenly distributed all through the weld region.

The SEM image and EDS results observed in the FDZ for all the joints are shown in figures 7(a)–(d). The EDS results of the AW joint (figure 7(a)) reveals that the main alloying element likes Mg, Si, Cr, Zn and Fe are completely dissolve in aluminium matrix during the welding. Although, a very high amount of heat generated in the weld region within a short period of time during FW may be the reason for the dissolution of alloying elements. Moreover, the highest percentage of Aluminum (90.41%) observed in AW joint when compared to ST, AA and STA joints. On other hand, the Zn (3.65%) and Cu (5.95%) present in the ST joint (figure 7(b)) found to be higher than the AA6061 (table 1) base metal. In addition to that, the significant amount of Fe (8%) also noted in the ST joint. The amount of Zn (15.32%) present in the AA joint is much higher with respect to all the joints and both the base metals. Further, the significant amount of alloying elements (Cu, Fe, Cr and Zn) presents in the AA joint resulted in the marginal improvement in tensile strength compared AW and ST joint. The concentration of main strengthening elements (Si, Mg, Zn, Cr, Fe and Cu) in STA joints (figure 7(d)) results the higher tensile strength over than all the joints.

Figure 4. Optical Microscope Parents metals & FDZ region of FW dissimilar joints (a) AA6061 PM (b) AA7075-T6 PM (c) AW joint (d) ST joint (e) AA joint (f) STA joint.
Figure 5. Micrographs of PDZ region at various conditions (a) AW- AA6061, (b) AW-7071, (c) ST-A6x, (d) ST-A7x, (e) AA-AA6x, (f) AA-7x, (g) STA-AA6x (h) STA-AA7x.
4. Discussions

The relation between the dislocation motion and mechanical behavior decides the hardness and strength of the non ferrous alloys. Moreover the strength may be enhanced by reducing the movement of the dislocation motion \cite{28, 29}. The reducing of dislocation motion obtained by formation of new phase particles (precipitates) and grain boundary. As per the Hall–Petch equation, the higher grain boundary (finer grains) will increase the hardness \cite{30, 31}. On the contrary, in the heat treatable alloys (AA6061 and AA7075 T6) the influence of finer grains on hardness is not much significant \cite{29}. This may be the reason that AW, ST and AA joints recorded the lower hardness value in weld region irrespective of finer grains. On the other side, disparate mixture of the both materials in the FDZ causes rapid variation in hardness from FDZ towards PDZ in AA6061 sides of all conditions. Because of parent metals hardness of AA7075 T6 condition is much higher than the AA6061 parent metal. Moreover precipitates act as hindrance to the motion dislocation during mechanical loading on the joints. Hence the resistance of plastic deformation by the finer (θ') precipitate particles resulted in increasing the strength and hardness.

Figure 6. TEM of parent metals & FDZ region of FW joints (a) AA6061 (b) AA7075-T6 (c) AW joint (d) ST joint (e) AA joint (f) STA joint.
4.1. As-welded joint

The strength obtained in the AW joint was lower than that of all other conditions and FDZ recorded the higher value of hardness as compared to HAZ zone of either side. Usually, AA6061 has lower hardness than AA7075.

Figure 7. SEM-EDS analysis at the FDZ region of the FW dissimilar joints.

4.1. As-welded joint

The strength obtained in the AW joint was lower than that of all other conditions and FDZ recorded the higher value of hardness as compared to HAZ zone of either side. Usually, AA6061 has lower hardness than AA7075.
Moreover the mixing of both these materials in FDZ resulted in higher hardness than AA6061. During the FW process, due to dynamic recrystallization occurrence in the FDZ resulting the finer grains which contribute the increase in the hardness. The dissolution of coarse precipitates in weld region during FW process could be the reason for the configuration of finer grains during recrystallization. AW joint fractured at PDZ of AA6061 side has the lower hardness value of 62 Hv. The presence of coarse precipitates in the PDZ during FW process may be the reason for the lower hardness. The evidence for softening of material in PDZ of AW joint confirmed through the ductile mode of fracture that is viewed in the fractographs figure 2(c).

4.2. ST joint
The hardness profile and tensile strength of ST joints were found to be lower than that of all other joints. Hence the ST conditions depreciate the mechanical properties in the all regions of joints. The joint fractured at HAZ region of AA6061 side has lower hardness value of 55 Hv and it may be attributed to the complete dissolution of finer precipitates (Mg2Si, AlMg and AlZn) in the aluminium matrix. The observed cleavages and the absence of precipitates in the TEM image (figure 6(d)) attributed towards the lowering all the mechanical properties. Overall it is concluded that solution treatment is not appropriate for the dissimilar joints to enhance the weld properties.

4.3. AA joint
Artificial aging relatively improves the mechanical properties as compared to AW and ST joints. The finer precipitates (AlZn & CuAl2) are to be seen in figure 6(c) and it will act as barrier to motion dislocation resulted in increased strength. EDS results (figure 7(c)) also reveal the same that the presence of strengthening elements like Zn, Cu and Cr are attributed to the formation of finer precipitates. These finer precipitates dissolved during FW process will re-precipitate during the aging treatment. Joint fractured at PDZ region of AA6061 side which has marginal improvement in grain size noticed in figure 4(e). Nucleation of grains during the artificial aging attributed towards the marginal improvement in hardness [32].

4.4. STA joint
The tensile strength recorded in STA conditions shows a significant improvement of the FW dissimilar joint and also with a fair enhancement in hardness profile than that of all other specimens. The increase of hardness will increase the strength of joint which already proven by many researchers. The STA allows the precipitates to re-precipitates as the finer \( \theta' \) particles (MgAl2, and CuAl2) in the FDZ along with coarse \( \theta \) precipitates (Al2CuFe). Due to the formation of these finer precipitates during STA treatment, the fine populated and shallower dimples are observed in fracture surface (figure 2(e)). The specimen experiences the partial annealing effect during the STA treatment might be the reason of high dislocation density in the PDZ region. Further, strain reduced in the PDZ of the STA joint due to annealing effect. This may be the reason for the joint to be fractured at the PDZ region.

5. Conclusions
From this investigation, the effects of PWHT on mechanical properties of FW dissimilar AA6061 and AA7075-T6 joints were studied and the following conclusions are derived.

Dissimilar aluminium alloys joint (AA6061 and AA7075-T6) has been fabricated successfully by friction welding. As-welded dissimilar joint deteriorates the tensile properties due to the dissolution of finer particles during FW process.

Solution treated joint, further lowers the tensile strength and hardness across the dissimilar welded joints. Artificial aged joint reveals some marginal improvement in mechanical properties across the weldment. Moreover, the STA joint exhibits the maximum tensile strength and hardness profile. This is owing to the uniform re-precipitation of finer particle over the entire (base metal, HAZ, PDZ and FDZ) joint.

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