Influence of Solution Treatment and Artificial Aging on Fracture Load of Friction Stir Welded Lap Joints of AA2014-T6

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Abstract. High strength aluminium alloys (2xxx and 7xxx) are widely used for many applications. Particularly, aircraft and automobile industries. The fabrication of this alloy is little bit difficult using traditional welding process. It produces porosity, alloy segregation, partially melted zone etc. In last few decades, these alloys are welded using a solid-state welding process, friction stir welding. However, the strength of the alloy is more than 80% of the base material strength. Although, the FSW joints have lowest hardness in the weld region due to heterogeneous properties in the microstructure. The lowest hardness region is the soft region that is the fracture-originating region during tensile test. Several techniques were used to enhance the lowest hardness region properties such as the aging process, the solution treatment process, cryogenic treatment in joints. In this research, the solution treatment followed by artificial aging on lap shear strength of friction stir lap-welded joints were performed. The heat-treated joints were compared with welded joints. From the experimental results, the heat-treated joints yield higher lap shear strength than the as welded joints. The reason for the higher lap shear strength was reprecipitation of precipitates in the welded joints during an artificial aging process. However, the aluminium matrix retains fine precipitates by the solution treatment process (under rapid cooling).

1 Introduction

High strength to weight ratio and corrosion prevention [1], high-strength Al alloys (7xxx, 6xxx and 2xxx series) are employed in many industries, including cars, aircraft and military vehicles. The welding of Al alloy-containing Cu (AA2014) is, however, a difficult task using a conventional welding method, as it results in hot shots, alloy segregation, improper melt in zones and clusters of pores [2]. In addition, there is a substantial decrease in strength [3] due to the growth of the dendritic structure in the welding area caused by traditional welding. FSW is a solid-state process of which hot shear joins metals. Non-consumable pin profiles of the tool are revolved and gently penetrate into the region around the overlapping sheet material's joint line. FSW is used to weld aluminium alloys, including the 2xxx and 7xxx series, which were previously considered to have low weldability characteristics. Aluminium alloy AA2014 is an age-hardened alloy and has characteristics such as high strength as a result of heat treatment processes such as quenching, tempering and artificial aging treatments due to the development of Al2CuMg and CuAl2 (Copper Aluminide) stages [4]. All the phases or precipitates previously formed are dissolved during FSW. However, a fraction of the precipitates was coarsened because of the applied thermal cycle in the thermo-mechanically affected zone (TMAZ). Although the FSW joints yields greater strength than fusion welded joints, as a result of precipitate distribution in the FSW joints. It was found that there was a significant reduction in the distribution of precipitates in the HAZ and TMAZ[5]by different welding speed.
Water cooling was investigated and its influence on the basic properties of AA2014, and the lowest hardness zone (LHZ) was observed on both side of work piece under different cooling conditions. However, the LHZ was located on different zones for air cooling and water cooling. The LHZ was, however, located in separate air and water-cooling zones. The LHZ was found in the HAZ for joint welding in air and in the TMAZ for joint welding in underwater FSW [6]. Rajendran et al. [7] stated that solutionization followed by aging was effective in restoring the joint’s tensile properties compared to treatments with AA and AW. Rajendran et al. [8] conducted on heat treatment experiments after welding on strength properties of AA2014 and reported solutionizing followed by aging improves strength of AA2014 alloy. From the observations [1-8], it is inferred that lot of research works have been focused toward heat treatment after weld. In this work, analyse the influence of solution treatment followed by ageing on fracture load in lap welded joints.

2 Materials and Methods

The Parent metal (PM) considered for this study was rolled AA2014 alloy sheets of 2 mm thickness. The sheet was cut in to 5 mm x 75 mm sections and locked in place tightly to establish lap joints structure. PM properties were confirmed as per the ASTM standard (Table 1 and Table 2).

| Table 1 Chemical composition (%wt.) of PM |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Cu   | Mn   | Si   | Fe   | Cr   | Zn   | Mg   | Ti   | Al   |
| 4.2  | 0.65 | 0.81 | 0.21 | 0.02 | 0.02 | 0.51 | 0.02 | 96   |

| Table.2 Mechanical properties of PM |
|-----------------|-----------------|-----------------|-----------------|
| 0.2 % YS (MPa) | UTS (MPa)       | % Elong. in 50 mm gauge length | Hardness (0.5 N, 15 s) |
| 432             | 460             | 7.5             | 152             |

Using FSW the joints were placed right angles to the sheets load direction. The shoulder diameter of 12 mm, tilt angle of 1.5 °, tool movement of 90 mm / min, and tool speed of 900 rpm are the optimal parameters used for manufacture of welds (Table 3). The joints were employed to solutioning (496 C for 1h.) followed by artificial ageing (160 C for 12 hr.) to enhance the strength of joints (Figue.1a, b).

| Table.3 Nomenclature FSW tool |
|-----------------|-----------------|-----------------|-----------------|
| D (mm)          | Type            | D₁ (mm)         | D₂ (mm)         |
| 16              | Concave         | 3               | 2               |

The lap shear specimens prepared in compliance with the specification ANSI / AWS / SAE / D8.97 [7] and the lap shear testing were performed at a slide movement of 1.5 kN / mm using UTM. High magnification microscopes (scanning electron and transmission electron microscopes) were employed to analyze the feature of various regions in welded joint. The elemental presences in the weld region were carried out using energy dispersive spectroscopy.
3 Results and Discussion

3.1 Lap shear strength

The shear fracture load of FSW joint and heat-treated joints is offered in Table 4. Three specimens were tested in each condition. PM exhibits a maximum shear fracture load of 18.34 kN. The heat-treated and as-welded joints yielded a maximum shear strength of 15.27 kN and 12.76 kN, respectively. It is observed that the heat-treated joints conceived higher lap shear strength than as welded joints. Figure 2a-c shows the optical micrograph of PM in as received condition and SZ of as weld and heat-treated joints. PM microstructure constituted rough and enlarged grains with a mean diameter of 30 μm.

Table 4. Lap shear strength of welded joints under different condition

| Sl.No | Condition                              | Microhardness “HV” | Fracture load “kN” |
|-------|----------------------------------------|--------------------|-------------------|
|       |                                        | SZ                 | AS-TMAZ | RS-TMAZ |                 |
| 1     | As weld joint                          | 123                | 106     | 115     | 12.76             |
| 2     | Solution treatment + artificial aged joint | 135               | 115     | 117     | 15.27             |
| 3     | As received                            |                    | 155     |         | 18.34             |

3.2 Microstructure

FSW joint is divided into three regions, such as thermo-mechanically affected zone (TMAZ), stir zone (SZ) and PM. Figure 2b shows the SZ micrograph of as welded joint. Similarly, SZ micrograph of heat treated joint as revealed in Figure 2c. SZ of both joints framed fine and recrystallized grains. The SZ of the heat-treated joint (Figure 2c) indicates a substantial increase in the size of the grain owing to a combination solution treatment process followed by an artificial aging process.
The microstructure of as welded joints in advancing and retreating sides TMAZ is exposed in Figure. 3a, b. Although, the microstructure of TMAZ in advancing side and retreating sides of heat-treated joint is shown in Figure. 3c, d. Both the microstructure under different conditions showed different grain sizes by material flow in retreating and advancing sides. Moreover, the grains in the advancing side of both conditions were revealed elongated and slanted to the upper side due to the pushing of plasticized materials in SZ by high straining action. The grains in the retreating side showed less slanted and coarsened in both conditions. The slanting and coarsening of grains happened by the velocity differences of plasticized material in the SZ by tool geometry and finer precipitates precipitated during heat treatment process [9].
3.3 Hardness distribution

The hardness of high strength aluminum alloy (2014) in as received condition showed a maximum hardness of 155 HV. Figure 4 show the hardness distribution of as welded and heat-treated joints and SZ of as welded joints and heat-treated joint exhibited a peak hardness of 123 HV and 135 HV, respectively. The hardness of the FSW joint is based on the size of the grains and spreading of precipitates. In the as welded joint, lowest hardness region was observed on both sides of advancing and retreating TMAZ. Similarly, heat-treated joints formed two lowest hardness regions on both advancing and retreating sides. The lowest hardness of 106 HV was recorded on the advancing side of as welded joint and 115 HV was observed on the retreating side TMAZ. In the heat-treated joint, the minimum hardness of 115 HV on the advancing side TMAZ and 117 HV on retreating side TMAZ were observed. The pattern of hardness distribution in the FSW weld is as symmetrical due to variation in the microstructure in the welded joint.

Figure 3 Optical micrograph of as weld joint a) AS-TMAZ b) RS-TMAZ, heat treated joint c) RS-TMAZ, d) AS-TMAZ
3.4 Fractograph

The fracture region of welded joints under different condition is presented in Table 5. The fracture region of as welded joint was occurred at HAZ and the fracture point of heat-treated joint was found at SZ/TMAZ interface. A close inspection of the failure surface of the specimen provides valuable data on the function and influence of the inherent micro-structural characteristics to the strength and ductility of the joint [10,11]. The crack morphology of tensile tested as shown in Figure.5a-c. SEM examination was recorded from the middle part of the fracture zone and characterizes the fracture morphology of the welded joints. Ultimately, FSW joint fracture occurred from the weaker region of the joints during the tensile test. Depending on the state of joints, the position of the soft region is found to differ from the TMAZ/SZ interface or HAZ. As welded joint separated from HAZ (115 HV) on the advancing side and the fracture position of the heat-treated joint was found in SZ/TMAZ interface. With deeper and larger dimples showing the as the weld joint fracture surface (Figure.5b). In the heat-treated joint (Figure.5c), which showed enlarged dimple surface, similar behaviour was also found; under tensile testing, these elongated dimples suggested fracture mode was ductile. The width of the dimples in the heat-treated joint was wide, it proposes that there is a large stretch area at the tip of the crack, leading to a massive plastic area ahead of the crack [8].

Figure. 4 Hardness distribution of FSW joints under different condition
Table 5 Fracture region of FSW lap joints

| Sl. No | Condition                                      | Joints               | Fracture Region |
|-------|------------------------------------------------|----------------------|-----------------|
| 1.    | As-weld joint                                  |                      | HAZ             |
| 2.    | Solution treatment + artificial ageing treated joint |                      | SZ/TMAZ         |

Figure 5 Fracture morphology of a) As received material b) As weld joint, c) Heat treated joint
3.5 TEM Micrograph

Two forms of precipitates (coarse and fine) were seen in the TEM micrograph of material in the obtained state (shown in Figure 6a). Rough precipitates differ in length from 60 to 110 nm, while fine precipitates differ in length from 20 to 60 nm with two distinct morphologies, including needle-like and spherical. Based on the EDS analysis, it is conformed that the fine precipitate was formed by Al, Cu and Mg elements. It suggests that the formation of Al<sub>2</sub>Cu (Figure 5d) and Al<sub>2</sub>CuMg (Figure 5e) precipitates. However, these precipitates were completely solutionized in the aluminium due to sliding heat in the weld cycle [12] except few coarse precipitates. The SZ of as welded joint showed complete fragmentation of coarse and fine precipitates (Figure 6b) and SZ of heat treated joint revealed fine dissolution of strengthening precipitate except few coarse precipitates (Figure 6c).

![TEM micrograph of a) Parent material, b) As welded joint c) Heat treated joint, EDS analysis of d) Particle A and e) Particle B.](image-url)
It can be concluded from the analytical outcomes, the morphology of strengthening particles were uniform compared to the as-welded joint. That is the explanation for heat-treated joints having a higher fracture load. The temperature of the solution is another significant factor in the regulation of grain stability in the FSW joints.

4. Discussions
The properties of FSW joints as a function of the process parameters, tool geometry, thermal cycle, and precipitate distribution and volume rather than grain size [13]. The strength of aluminum alloys has improved by many techniques after welding. SZ of FSW joints experienced by severe heat input in the range of 300 C to 480 C [14,15]. During this period, the precipitates were dissolved in the aluminum matrix completely. Whereas, in the HAZ on both retreating and advancing sides experienced by partial heat input. Moreover, this heat input makes the precipitates coarse in size, even though the PM grains were not altered during thermal cycle [14]. Hence, this coarsening action is the weakest region in as-weld condition. Ageing treatment is the most effective method of precipitation of precipitate, which increases strength compared to the as-welded joint. Moreover, in the FSW process, the precipitates become rough or dissolve and this result reduces the joint's strength. The heat treatment significantly improved the properties of the lower hardness in the as-welded joint. The heat-treated joints offered better strength (15.27kN) compared to the as-welded joint. Solution treatment and artificial ageing process enhanced the size of grains in all regions, resulting in the size of grains increases in aluminum matrix. The formation of new grains in larger size is caused by the heat treatment process [16]. Dense and thick distribution of precipitates were observed in the weld region. Hence, the heat-treated joints yielded higher shear strength than as-welded joints. Abnormal grain growth is the other phenomena in all FSW joints that have occurred in the weld due to inhomogeneous plastic deformation during the thermal cycle. Due to abnormal grain growth, it causes a) antistrophic in mobility and grain boundary. b) reduces the anchoring effect of precipitates in the grain by the solutioning process. The solutioning temperature is another factor, which will promote larger grains when the temperature is high. In this investigation, the solution process was performed at 496 C and 1 h holding time.

As per the Hall–Petch relationship, the weld strength depends on the grain size and precipitates distribution. Although, the hardness distribution in the weld is direct relationship with the welding strength. All the FSW joints are invariably formed by different microstructure in the weld region. This heterogeneous property was formed by thermal cycle during FSW. SZ region experienced by severe heat input and whereas HAZ experienced by lower heat input (250 C). This difference in heat input is the reason for a symmetric flow pattern in the FSW joint. The lowest hardness region of as welded joint was observed at the HAZ on both advancing and retreating sides. The soft region was formed by the dissolution or coarsening of precipitates during FSW cycle. Because the SZ of welded joints was homogenized by thermal cycle between 420 C and 480 C and causes the dissolution of strengthening precipitates (Al2Cu). Precipitate dissolution is the cause for the formation of lower hardness at HAZ in as-welded joint. Heat treated (Solution treatment followed by ageing process) joints possess peak hardness in HAZ, TMAZ and SZ. Heat treatment is associated with the increase size fraction of dissolved particle that enhances the presence of alloying element for re precipitation during ageing treatment, the lap shear strength of FSW joints in the as-welded condition offers inferior strength than heat treated joint. The reason for the existence of high lap shear strength in heat-treated joints is abnormal grain growth. The abnormal grain growth is a metallography transformation of which few grains progress abnormally at the expenditure of fine alpha matrix grains and it occurs when the regular grain progress stationary [17]. The formation of abnormal grain growth in the SZ has a substantial effect on lap shear strength of FSW joints further heat treatment. The formation of precipitate in as welded joint has been shown in coarse in size by agglomerating precipitate during thermal cycle. The reduction in dislocation density and coarsening of precipitates causes lower hardness and increasing lower hardness width as welded joint. The width of the lower hardness on HAZ in heat-treated joints was reduced and moved toward the weld center due to artificial ageing in the heat treatment process. The ageing process enhances the re precipitation of precipitates (θ’) [18,19].
5. Conclusions

The friction stir lap-welded joints were successfully heat-treated using two techniques namely solution treatment followed and artificial aging process. The lap shear strength of the joints was correlated with heat-treated joints in systematically. The heat-treated joints conceived higher lap shear strength than the as welded joints, due to the recovery of lost strength in the lowest hardness region (soft region). The solution process was performed at 496 °C for soaking period of 1 h make complete solubility of solute (Al2Cu) and retains the same by rapid cooling. The ageing process was performed at 160 °C and soaking period of 12 h. The artificial ageing process promotes re-precipitation of precipitate in the weld region. Hence, the lowest hardness region in the heat-treated joints was minimized. The abnormal grain growth has substantial effect in lap shear strength of FSW joints after heat treatment.

References

[1] ZhouC. YangX., LuanG.2006 Effect of root flaws on the fatigue property of friction stir welds in 2024-T3 aluminium alloys. Mater. Sci. Engg. A, 418,155-60.
[2] SquillanceA. De RenzoA, Giorleo G, Bellucci F, 2004 A comparison between FSW and TIG welding techniques: modification of microstructure and pitting corrosion resistance in AA2024-T3 butt joints, J Mater. Process. Tech, 152,97-105.
[3] Genevosis C, Deschamps A, Denquin A, Doisneau-coottignies B,2005, Quantities investigation of precipitation a mechanical behavior for AA2024 friction stir weld, Acta Mater, 53, 2447-58.
[4] Liu.H, J, Zhan.L. L, 2011, Effect of welding speed on microstructures and mechanical properties of underwater friction stir welded 2219 aluminum alloy, Mater. Design, 32,1548-1553.
[5] Zang Z, Xiao,Z. Ma Y,2014, Influence of water cooling on microstructure and mechanical properties of friction stir welded 2014 aluminum alloy, Mater.Eng.A, 614, 6-15.
[6] Wang Ji, Ruidong Fu, Yiium Li, Jianfeng Zang,2014, Effect of deep cryogenic treatment and low temperature aging on the mechanical properties of friction-stir-welded joints of 2024-T351, Mater.Sci. Eng A, 609, 147-153.
[7] RajendranC,Srinivasan K, Balasubramanian V, Balaji H, Selvaraj P,2019, Effect of Post Weld Heat Treatment on Strength and Microstructure of Friction Stir Welded Lap Joints of AA2014-T6 Aluminum Alloy. Metal Science and Heat Treatment 61,5-6,305-310.
[8] Rajendran C, Srinivasan K, Balasubramanian V, H.Balaji, P.Selvaraj, 2016, Influence of post weld heat treatment on tensile strength and microstructural characteristics of friction stir welded butt joints of AA2014-T6 aluminium alloy, J Mech Behav Mater, 25(3-4): 89-98.
[9] Chaitanya Sharma, dheerendra Kumar Dwivedi, Pradeep Kumar 2013 Effect of post weld heat treatment on microstructure and mechanical properties of friction stir welded joints or Al-Zn-Mg alloy by AA7039, Mater. Design, 43, 134-143.
[10] SrivatsanT S, Vasudevan S, Park L, 2007, Tensile deformation and fracture behavior of friction stir welded aluminum alloy 2024. Mater.Sci.456, 235-45.
[11] Suvillian, A, Robson J D,2008, Microstructural properties of friction stir weld and post welded heat treatment 7449 aluminum alloy thick plate, Mater. Sci. Eng A, 478 (1-2), 351-60.
[12] Rajendran, C.Srinivasan K, Balasubramanian V, Balaji H, and Selvaraj P, 2019 Evaluation of load-carrying capabilities of friction stir welded, TIG welded and riveted joints of AA2014-T6 aluminium alloy. Aircraft Engineering and Aerospace Technology.
[13] Attallah, M Moataz., and G Hanadi. Salem. 2005 Friction stir welding parameters: a tool for controlling abnormal grain growth during subsequent heat treatment. Materials Science and Engineering: A 391, 1-2, 51-59.
[14] Rhodes, C. G, MahoneyM. W., BingleW. H., SpurlingR. A., and BamptonC. C 1997 Effects of friction stir welding on microstructure of 7075 aluminum. Scripta materialia 36, 1, 69-75.
[15] MahoneyM. W, RhodesC. G., FlintoffJ. G., BingleW. H., and SpurlingR. A.1998, Properties of friction-stir-welded 7075 T651 aluminum. Metallurgical and materials transactions A 29, 7, 1955-1964.

[16] Rajendran, C., K. Srinivasan, V. Balasubramanian, H. Balaji, and P. Selvaraj. 2019 Effect of tool
tilt angle on strength and microstructural characteristics of friction stir welded lap joints of AA2014-T6 aluminum alloy. *Transactions of Nonferrous Metals Society of China* 29, 9, 1824-1835.

[17] Safarbali, B., M. Shamanian, and A. Eslami. 2018, Effect of post-weld heat treatment on joint properties of dissimilar friction stir welded 2024-T4 and 7075-T6 aluminum alloys.” *Transactions of Nonferrous Metals Society of China* 28, 7, 1287-1297.

[18] Rui-dong Fu, Jian-Feng Zhang, Yi-jun Li, Ju Kang, Hui-Jie-Liu, Fu-cheng Zhang, 2013, Effect of heat input and post welding natural aging on the hardness of stir zone for friction stir welded 2024-T3 aluminum alloy thin sheet, *Mater. SciEng A* 599, 319-324.

[19] Ji Wang, Ruidong Fu, Yijun Li, and Jianfeng Zhang. 2014, Effects of deep cryogenic treatment and low-temperature aging on the mechanical properties of friction-stir-welded joints of 2024-T351 aluminum alloy, *Materials Science and Engineering: A* 609, 147-153.