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Post weld heat treatment of continuous drive friction welded AA6061/SiC/graphite hybrid composites—an investigation

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Abstract

The continuous drive friction welding is a solid state, environment friendly welding method employed to join ferrous and non-ferrous materials. The paper aims at producing better quality joints using AA6061/SiC/graphite hybrid composite using continuous drive friction welding with post weld heat treatments. It investigates the effect of post weld heat treatments including solution treatment (ST) and solution treatment followed by ageing (STA) on mechanical and microstructural characteristics of continuous drive friction welded hybrid composite joints. The tensile properties were evaluated along with micro hardness and correlated with the microstructural characteristics with the primary focus on comparing the as-welded (AW) and post weld heat treated joints. The joint efficiency of STA joint is 73.82% and the ultimate tensile stress is 189 MPa. Final observations revealed that the grains appear relatively finer in the weld zone of the joint and increase in hardness after STA treatment. This may be the reasons for superior performance of STA joints and preferable microstructural characteristics compared to the ST and AW joints.

1. Introduction

The superior mechanical properties allow the usage of ceramic particle reinforced aluminium in aerospace and automobile industries. The aluminium alloys used in aircrafts generally exhibit low weldability in traditional fusion welding methods. An enhanced urge to study their welding characteristics has become essential in broadening their engineering applications. The specific applications include valve rods and propeller shafts [1]. The main challenge lies in joining them with limited microstructural abnormalities and metallurgical changes. The ceramic particles were found to react with the matrix materials at fusion state to produce undesirable changes in the joints [2, 3]. A wider heat affected zone (HAZ) in a highly conducting material like aluminium alloy is an unwanted feature in a joint. Further solidification cracking, fissuring and hot tearing are commonly observed problems in fusion joints with aluminium alloys. These undesirable features in a welded joint could be kept in check by employing a solid state welding process like continuous drive friction welding. The process operates on the principle of restricting the temperature at the interface to a considerably lesser value than the melting point of the parent material, ensuring a lesser HAZ and production time [4]. The weld is formed as the rotating half of the joint is pressed against a static part to produce the required thermal input at the interface. The frictional heat at the interface along with the axial pressure guarantees a deformation closer to the joint interface. The soundness of the joint depends upon the main parameters of the process which includes frictional pressure, burn off length, upset pressure and the rotational speed. Many studies have observed the effects of these individual parameters and their interactions [5]. The 5A33 Al alloy to MgAZ31B alloy joints displayed a reasonably good strength at increasing friction time but the fracture mode is predominantly brittle and an increased micro hardness was observed at the interface [6]. The thermo-mechanically affected zone (TMAZ) showed reduced hardness of matrix during friction welding of cast AlSi/SiCp metal matrix composites [7]. A joint efficiency of 89% could be achieved in as-welded condition with proper selection of process variables using AA7075-T6 aluminium alloys. However a higher joint strength could be achieved using post weld heat treatments (PWHT) in joints formed with optimal parameters [8, 9]. Over an increasing range of ageing times, the
transverse tensile strength of naturally aged 7050Al alloys increased continuously along with an improved hardness [10]. Deformed zone and recrystallized zone were observed at the interface of metal-ceramic joint and the deformation level was higher in the metal part of the joint [11]. Fracture was observed along the weld interface during uniaxial tensile loading of joints. Among various parameters, the friction time played a vital role in forming good joints [12]. The microhardness was found to be more uniform and increases with precipitate distribution in aluminium alloy friction welded joints subjected to heat treatment [13].

The post weld heat treatment (PWHT) including ageing or solution treatment followed by ageing was observed to improve yield strength of the joints by forming fine precipitates. The post heat treatment could improve the tensile strength of friction welded aluminium alloys [14]. T6 (190 °C–10 h) ageing treatment performed on the 2024-T4 friction stir-welded joints had enhanced the tensile properties excluding the ductility of joint, but a drop in microhardness along the weld zone is also seen [15]. The solution treatment followed by artificial ageing was found to be beneficial compared to artificial ageing in increasing the tensile strength of friction welded AA7075-T651 aluminium alloy [16]. However a simple artificial ageing was observed to enhance the tensile properties of AA6061 aluminium alloy joints [17]. The PWHT was also observed to decrease the ultimate strength of welds formed with Al–Zn–Mg joints. This could have a significant impact as the yield strength was also decreased but the elongation was improved surprisingly [18]. The tensile strength depends on the increase of reinforced SiCp particle and volume fraction [19].

A comparison of fusion welded joints with the joints formed in solid state had revealed the pronounced and beneficial effects of PWHT on fusion welded joints. An improved elastic modulus along with significantly improved mechanical properties, accompanied by a homogenous microstructure in the weld zone was evident in fusion welded joints [20, 21]. During friction welding of AZ61 alloy and subsequent PWHT, ageing period was found to play a major role in improving the joint efficiency along with the temperature. The coarse grains observed after PWHT and precipitate free zones could be attributed to the brittleness of the joints [22, 23]. Weld centre possessed equiaxial grains, while grains appeared highly deformed in thermo mechanically affected zone. The fracture toughness of both the zones increased significantly after PWHT [24]. Studies on dynamic recrystallization, re-precipitation and dissolution have shown the important role played by solutionizing temperature [25, 26]. Re-precipitation was observed to increase the hardness, while recrystallization of finer grains enhanced the strength. No significant grain distortion was observed during recrystallization [27]. The solutionizing could dissolve eutectic constituent Mg2Si and make the zone more homogenous leaving behind the composite particles of SiC and graphite unaffected. As the strength of the weld due to ST, has not shown substantial improvement, it is preferred to carryout STA. As AA6061 is precipitation hardening alloy, the heat treatment of STA, should improve bonding strength at the weld Zone.

However, more investigation is needed to find the effective measurements for enhancing the mechanical properties of friction welded joints. PWHT could effectively enhance the tensile properties by improving the microstructure. Limited literature is available in studies related to the effect of PWHT and its effects on AA6061/SiC/graphite hybrid joints. Hence an investigation of solution treatment (ST) and solution treatment followed by ageing (STA) on the tensile and micro structural characteristics on continuous drive friction welded hybrid composite is carried out and the results are presented. This investigation could assist in bringing the positive effects of PWHT to friction welded hybrid composites and promote their engineering applications.

2. Experiment

2.1. Materials

AA6061 was chosen as the composite matrix since it finds noteworthy applications in the field of aerospace and automobile engineering. The matrix was reinforced with fine particles of silicon carbide (SiC) and graphite (Gr) in weight fractions of 10% and 5%, respectively. The chemical composition of AA6061 is given in table 1.

| Chem. | Mg | Si | Fe | Cu | Cr | Mn | Zn | Ti | Al |
|-------|----|----|----|----|----|----|----|----|----|
| (wt%) | 0.9 | 0.62 | 0.33 | 0.28 | 0.17 | 0.06 | 0.02 | 0.02 | Bal |

2.2. Fabrication of composites

In-situ fabrication method was employed by dispersing the reinforcements in liquid Al6061 alloy at 650 °C after removing the slag. Both the reinforcement particles(SiC and Gr) were preheated at 150 °C to improve wettability and remove moisture from them. Magnesium (2%) was also added to improve the wettability. The stir casting facility employed to obtain cast samples is shown in figure 1. The aluminium melt furnace can handle up to 7 Kg
aluminium and is fitted with a motorized stirrer (0 to 500 rpm). A double stage stirring was performed to ensure a homogenous distribution of graphite and SiC particles.

The cast samples of length 45 mm and diameter 16 mm were machined and subjected to hot extrusion process, carried out at a preheating temperature 450 °C. Hot extrusion produces a higher level of deformation in
parent material creating important modifications in mechanical properties and microstructure. The process also induces residual stresses in the parent material. The extrusion set up is shown in figure 2(a). The D2 tool steel die used for extrusion along with punch is displayed in figures 2(b), (c). The extruded specimens are machined to a length of 60 mm and diameter 12 mm.

The microstructure of the extruded sample is observed after preparing the metallographic specimen by using standard technique and etching using the Keller’s reagent for 22 s. Optical microscope is used to perform microstructural analysis at 200X magnifications. The FE-SEM image of the parent material (Al6061/SiC/Gr) is shown in figure 3, wherein uniform distribution of reinforcements is observed. The average size of reinforcing particles is in the range of 60 to 80 microns. The EDAX analysis of the extruded parent material is shown in figure 4(d). It shows the concentration of various atomic species with the horizontal axis showing the energy level and the vertical axis displaying the count of characteristic x-rays beams. The individual phases in the parent material are evident in the EDAX image. Fractured primary and secondary arms of dendrite carrying the alpha grains of AA 6061 are visible on the sample edge (figure 4(a)), along the direction of extrusion. The reinforcements are trapped in the junction of the arms (figure 4(b)). The elongated grains of dendrite are visible in the core of specimen along the direction of extrusion (figure 4(c)).

2.3. Welding
The extruded specimens were joined in a continuous drive friction welding machine (model: SPM-FW-3T) shown in figure 5(a). The maximum speed of the machine spindle was 2000 rpm and the clamping was done in a hydraulically controlled chuck. The machine has a Rexroth controller and was inbuilt with a data acquisition and analysis software. The trial runs were performed to identify the parameters that could produce a defect free weld at a macro level. Friction welding was carried out at a rotational speed of 1600 rpm and at an upset load of 3.5 kN for 3 s. The joints were made by bringing the specimens in contact with pressure, generating the frictional heat by rubbing action. In total 24 joints were manufactured and friction welded joints were shown in figure 5(b).

2.4. Post weld heat treatment
The eight joints were kept in as-welded (AW) condition without post weld heat treatment (PWHT), while the others were subjected to heat treatment in a muffle furnace (Model: VBBF-1200) with Kanthal heating element capable of generating 1200 °C at a rate of 20 °C min⁻¹. The PID programmable digital temperature controller can perform the heat treatment with the desired degree of accuracy. Solution treatment (ST) was performed on eight joints by raising the temperature of joint to 525 °C. Solutionizing to form a homogenous solid solution is the primary step of precipitation hardening. After soaking for a period of one hour, the joints were quenched in water. Remaining eight specimens were solution treated followed by artificial ageing (STA), wherein the solutionized samples were aged at 163 °C for 8 h.
2.5. Microstructure analysis

The optical micrographs of the weld line, weld zone and TMAZ were captured for AW, ST and STA joints employing standard metallographic procedures. Cooled Keller’s reagent was used as the etchant to reveal the microstructure. The microstructural analysis was performed by using a 100 W halogen powered optical microscope (model: MM-400/800), with a maximum magnification range of 10X to 400X.

2.6. Micro hardness survey

Vickers’ micro hardness tester was used to measure the hardness variations across the weld-cross-section by applying a load of 0.2 Kg and a dwell time of 15 s. The micro hardness measurements were taken in transverse sectioned specimen, starting from the weld centre line to the thermo mechanically affected zone (TMAZ) on both the advancing and rotating side of the joint.

2.7. Tensile properties evaluation

The Tension test was performed in a screw driven universal testing machine (Model: FMI-F-100) capable of applying a maximum load of 100 kN. A strain gauge based load cell can measure the load with desired precision and accuracy. The tensile specimens were machined to the standard dimensions and the tension test was performed both in notched and un-notched specimen as per ASTM B557 standard. The specimen layout is displayed in figure 6 and the images show a few fractured specimens (figure 7(a)-notched and 7(b)-un-notched).

3. Results and discussion

3.1. Macrostructure of weld joints

The longitudinal section of the weld zone displaying the flash (macrographs) of a few friction welded joints is shown in figure 8. The plastic flow of material because of the generated frictional heat is evident at the bond interface. The material has flown outward as flash and has curled inside as the required upset pressure is applied.
Figure 5. (a) Friction welding machine (b) friction welded samples.

Figure 6. Layout of un-notched and notched tensile specimen.

Figure 7. Fractured tensile specimen (a) notched (b) un-notched.
to form the bond. The weld line is not so identifiable which indicates the goodness of the bond. The flash is removed in all the joints before subjecting them to various tests.

3.2. Microstructural analysis
During tensile test, all the specimens failed at TMAZ region, irrespective of post weld heat treatment. This is mainly due to the lowest hardness of TMAZ region compared to other regions and it is evident from microhardness survey. To understand the reason for lowest hardness distribution at TMAZ region, microstructure analysis was carried out and the optical micrographs of various regions of the joints are displayed in figure 9. From the micrographs it is clear that the weld line of all the joints contain finer grains and this is mainly due to occurrence of dynamic recrystallization. This may be one of the reasons for higher hardness recorded at weld line. Similar trend was observed in case of optical microscopy analysis of the weld zone which extends to a distance of 1 mm on either side of the bond line but the grains are marginally bigger compared to weld line but smaller than parent metal. This is mainly due to the dynamic recrystallisation occurred in this region is not complete. This may be one of the reason for slight decrease in hardness at weld zone but higher than TMAZ region. The ST and STA treated samples showed finer grains of primary aluminium alloy. Much finer particles in the TMAZ of STA is observed compared to the ST sample. During the ST and STA treatments, rapid cooling could have led to the formation of finer grains. Final observations reveal that the grains appear relatively finer after STA treatment, hence increased tensile strength of STA joints.

3.3. Micro hardness
The average hardness values plotted for AW, ST and STA joints is displayed in figure 10. No significant variation in micro hardness is observed on the rotating and advancing halves of the joints in all cases (AW, ST and STA). Generally, the micro hardness values are observed to be greater at weld lines and in weld zones, which generally extend to a length of 1.5 mm on both sides of weld. The values were observed to drop further beyond the weld zone while moving across the TMAZ on both sides of the weld line. The STA joints displayed the highest hardness in all the zones compared to the AW and ST joints.

3.4. Tensile properties
The transverse tensile properties of the friction welded joints are presented in table 2. In each condition, three specimens were tested and average of the results is presented in table 2.

The tensile strength (TS) and yield strength (YS) of un-welded and extruded parent material (Al6061/SiC/Gr) are 256 MPa and 221 MPa respectively. The total elongation is observed to be 6.51%. However, the TS and YS of
AW joints, prior to heat treatment shows a considerable decline in values (TS- 167 MPa and YS- 147 MPa). Further there is a decrease in ductility of the joint and it is observed in terms of an elongation of 4.5% and it is lesser compared to parent material (6.51%). Similar observations were made earlier in literature [14, 16, 18, 28]. The ST joints have shown further decrease in strength (TS- 156 MPa and YS- 140 MPa) and elongation (3.02%) compared to the AW joints. The reduction in tensile strength is 7% compared to the AW joint and this led to significant decrease in joint efficiency (60.93%). However, the STA joints displayed better tensile properties (TS- 189 MPa and YS- 157 MPa) compared to the AW and ST joints. On comparison with the ST joints, the STA joints displayed an improvement in joint efficiency by 13%. However, this is accompanied by a decrease in ductility (2.77%). It is noteworthy to observe that the notch strength ratio (NSR- ratio of tensile strength of notched and un-notched specimen) values are greater than one for all the joints. This suggests that all the joint fall under ‘notch
ductile' material category, i.e., the presence of notch in weld zone does not affect the ‘notch ductile’ behaviour of the material.

3.5. Fractured surfaces

The FE-SEM images of fractured tensile (un-notched) specimen are displayed in figure 11. Scanned images are taken on the fractured surfaces perpendicular to the direction of uniaxial loading in cases of AW, ST and STA specimens. The fractured surface of AW shows large grains with random presence of Al₂O₃ particles. Al₂O₃ was formed due to oxidation during welding. The higher resolution magnification at 1000X shows orientation of
grains along the direction of friction weld rotation. No uniform fracture surface morphology observed. The fractured surface of ST and STA display more uniform and fine-grained morphology. The effect of heat treatment resulted in the formation of homogenous matrix. Hence fractured surface shows more uniform and fine-grained structure. The higher magnification of 1000X of ST and STA resolved the uniform fine dimples.

Comparison of ST and STA fracture surface micrograph shows almost uniform presence of dimple density at the fracture. The fractography images of AW samples showed large crests and troughs while the STA joints showed fine grained structure. This could be attributed to the higher tensile strength of STA joints.

4. Conclusions

The research work presents an informative report on the effects of PWHT on mechanical and microstructural characteristics of continuous drive friction welded-solid state joints formed with AA6061/SiC/graphite hybrid composites. The influence of ST and STA treatments on the joints were studied and the following conclusions are gained.

- The Tensile strength and Yield strength of AW joints (prior to PWHT) showed a significant descent compared to those of the extruded parent material. The ST joints were observed to exhibit a further decline in strength (6.58%) and elongation (3.31%) compared to the AW joints. This could be attributed to the coarsening of grains in weld zone aided by the contributions from brittle reinforcements.
- The weld joints subjected to STA treatment displayed a higher tensile strength than the ST and AW joints by 21.15% and 13.17%, respectively. Though this is accompanied by a decrease in ductility, the NSR values are greater than unity (1.1400) proving notch strengthening and hence the ductile nature of parent material.
- The STA joints displayed the maximum hardness in the weld zone and TMAZ on comparison with the AW and ST joints. However, the microhardness values were observed to drop while moving away from the weld zone and further away from TMAZ in both the advancing and rotating halves of the joint.
- The AW samples suffered rapid heating and cooling that led to the segregation of composite constituents. The ST and STA joints due to solutionizing resulted in the production of homogenous matrix.
- The tensile properties of AW joint decreased because of coarser grains at weld zone. The optical microscopy studies reveal relatively finer grains after STA treatment compared to AW and ST joints, resulting in a reasonable recovery of tensile properties.
- The future scope lies in identifying the optimal solution temperature and time for further improvement in mechanical properties and microstructural characteristics of solid state AA6061/SiC/graphite hybrid composite joints. This will serve a long way in enhancing the engineering applications of these joints.

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