Welding of Al6061 and Al6082-Cu composite by friction stir processing

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Abstract. Present study aims at investigating the influence of process parameters on the microstructure and mechanical properties such as tensile strength and hardness of the dissimilar metal without and with copper powder. Before conducting the copper powder experiments, optimum process parameters were obtained by conducting experiments without copper powder. Taguchi’s experimental L\textsuperscript{9} orthogonal design layout was used to carry out the experiments without copper powder. Threaded pin tool geometry was used for conducting the experiments. Based on the experimental results and Taguchi’s analysis it was found that maximum tensile strength of 66.06 MPa was obtained at 1400 rpm spindle speed and weld speed of 20 mm/min. Maximum micro hardness (92 HV) was obtained at 1400 rpm spindle speed and weld speed of 16 mm/min. At these optimal setting of process parameters aluminium alloys were welded with the copper powder. Experimental results demonstrated that the tensile strength (96.54 MPa) and micro hardness (105 HV) of FSW was notably affected by the addition of copper powder when compared with FSW joint without copper powder. Tensile failure specimen was analysed using Scanning Electron Microscopy in order to study the failure mechanism.

1. Introduction

Recently, Aluminium alloys are significantly used in aircrafts structures, yacht building, automotive parts due to its high strength to weight ration and resistance to corrosion properties. Aluminium alloy is highly weldable in resistance arc welding and tungsten inert gas welding (TIG), but fusion welding of dissimilar aluminium is tedious. In order to overcome short comes of traditional welding method a friction stir welding is a new revolutionary technique developed by Wayne Thomas at TWI (The Welding Institute). Friction stir welding is widely used to join similar and dissimilar metals because of its advantage over the other conventional methods. A various parameters such as rotational speed, welding speed and tool geometry etc. are plays very important role in friction stir welding [1-3].

Most of researchers [1-5] studied effect of FSW process parameters such as rotational speed, welding speed and design of tool pin etc. on welding of similar and dissimilar metals. Omar et al. reviewed the state-of-the-art of FSW of aluminium matrix composite materials. They found welding parameters such as tool rotation speed, traverse speed, and axial force have a significant effect on the amount of heat generation and strength of FSW joints [6]. Zhang et al. [7] observed that the grain size of the nugget zones decreased with the increasing welding speed or the decreasing tool rotation rate. The greatest ultimate tensile strength of 484 MPa and largest elongation of 9.4 were obtained at 350 rpm with 100 mm/min and 350 rpm with 50 mm/min, respectively. The ultimate tensile strength and elongation deteriorated drastically when rotation rate increased from 350 to 950 rpm at a constant welding speed of 100 mm/min. But for the material AA6065, the highest tensile strength is reached in correspondence to the higher rotating speed (800 and 1000 rpm) and the highest welding speed (80 mm/min), which is contrary result to Zhang et al., [7] observed by Cavaliere et al. [8]. It implies that joining material also plays the important role in order to optimize the welding process parameters.
Same author Cavaliere et al. studied the effect of welding speed (with advancing speed in the range 40–460mm/min) on the mechanical and microstructural properties of AA6082. A strong variation in the nugget grain size was observed by increasing the advancing speed from 40 to 165mm/min up to a plateau corresponding to no further variations by increasing the speed up to 460 mm/min [9]. Rodriguez et al. [10] concluded that, lower and even higher rotational speeds are not suited for the maximum mechanical strength. An inspection of the fracture surfaces suggested that inadequate material intermixing produced at low tool rotational speeds was the cause for the low mechanical strength and failure through the stir zone. On the other hand, the failure observed through the heat-affected zone at high rotational speeds was produced due to the material softening as confirmed from the micro hardness measurements. Also grain growths resulting from temperature rise during FSW in nugget zone are responsible for the lower mechanical strength. However, for the low tool rotational speed, failure occurred in the stir zone due to poor material intermixing. Further research will focus on the optimization of the joint strength and its fatigue properties.

Besides, rotational speed and welding speed, the tool geometry and material positions are also important parameters which influence on the performance on the welded joints. Guo et al. successfully joined dissimilar aluminium AA6061 and AA7075 alloy using friction stir welding. It concluded that the material mixing is much more effective when AA6061 alloy was located on the advancing side. The highest joint strength was obtained when welding FSW conducted at highest welding speed and AA6061 plate was fixed on the advancing side [11]. Llangovan et al. studied three different tool pin profiles like straight cylindrical, taper cylindrical and threaded cylindrical. It concluded that threaded pin profile of tool contributes to better flow of materials between two alloys. It also resulted, higher hardness and higher tensile strength in the stir zone compared with other two profiles. The increase in hardness is attributed to the formation of fine grains and intermetallic in the stir zone [12]. Also Sadeesh et al. found that the cylindrical threaded pin and squared pin tool profile were found to be the best among other various pin profiles includes cylindrical threaded pin, cylindrical pin, squared pin, tapered pin and stepped pin tool profiles that were considered for the joining of AA2024 and AA601 aluminium plate of 5 mm thickness [13]. Dawood et al. studied the effect of small tool pin profiles on microstructures and mechanical properties of 6061 aluminium alloy by friction stir welding. It is observed that the smaller tool pin profile and shoulder diameter lead to narrow region of heat affected zone (HAZ) and a desired level of softening [14]. Besides the joint strength, wear and corrosion properties are also get influenced by the welding process parameter such as rotational speed and welding speed (Wang et al.) [15]. From literature review it is found that, welding process parameter must be in the specific range in order to have the good welded joints. Aim of this study is to identify the welding process parameters for obtaining good weld strength and hardness. To investigate the effect of copper powder addition in the weld zone on the weld strength.

2. Materials and Methods
In the present study aluminium alloy of AA6061 andAA6082 grade was welded without and with copper powder. Aluminium alloy of size 55 mm x 50 mm x 6 mm was considered for the experiments. Copper powder of 325 mesh size was used for the experimentation. An edge preparation of the specimen was carried out when the experiments were conducted with the copper powder. Edge preparation includes a chamfer of 1 mm depth with 45° angle on both the plates. This was done to prevent the powder being thrown out of the specimen during welding process. High carbon high chromium (D2) material was used as the tool material for the experiments. Tool has shoulder of 18 mm diameter and threaded (M6) pin of 5.5 mm length. Figure 1 shows the experimental setup. Experiments were performed on conventional milling machine and butt joint configuration was used for welding process. Initially the plates were held in position using mechanical clamps. Spindle speed (1000 rpm, 1400 rpm and 2000 rpm) and welding speed (16 mm/min, 20 mm/min and 25 mm/min) were set manually on the machine.
Taguchi’s $L_9$ orthogonal array was used to carry out the experiments and to identify the optimal setting of process parameters. Table 1 shows the experimental design layout as per Taguchi’s method. During this set of experiments no powder is used.

**Table 1.** Experimental layout with observed values.

| Spindle speed (rpm) | Welding speed (mm/min) | Ultimate tensile strength (MPa) | Hardness (HV) |
|---------------------|------------------------|--------------------------------|---------------|
| 1000                | 16                     | 53.34                          | 74            |
| 1000                | 20                     | 56.89                          | 68            |
| 1000                | 25                     | 64.62                          | 74            |
| 1400                | 16                     | 60.65                          | 92            |
| 1400                | 20                     | 66.06                          | 86            |
| 1400                | 25                     | 63.49                          | 80            |
| 2000                | 16                     | 54                             | 86            |
| 2000                | 20                     | 54.88                          | 86            |
| 2000                | 25                     | 35.54                          | 80            |

Hardness of the cross-section at the surface was measured using a Vickers hardness tester (Omnitech) with a load of 200 g on the work piece along the area perpendicular to the weld pool. The tensile strength was measured using a universal testing machine. The appearance of a cross-section was observed after polishing and etching with Keller’s reagent. The microstructure was investigated using a scanning electron microscope (Hitachi SU-70) in order to observe the defects and the dispersion of the powder in the stir zone.
3. Result and Discussions

3.3.1. Mechanical properties without copper powder

This study depicts the mechanical behaviour of Al6061-Al6082-Cu composites. Tensile strength of the stir butt welding joints in all welding condition at room temperature is shown in figure 2. Experimental results demonstrated an apparent increase in tensile strength of the joint with the increase in rotational speed, but at higher speed 2000 rpm it decreases, irrespective of the welding speed from 16 to 25 mm/min. The highest tensile strength is reached in correspondence of the spindle speed of 1400 rpm and welding speed of 20 mm/min. For lower spindle speed i.e.1000 rpm, the tensile strength increases with increasing the welding speed from 16 to 25 mm/min, on the contrary it decreases as the spindle speed increasing to 2000 rpm. Higher rotational speed (2000 rpm) and the highest welding speed is the worst combination for the stir butt weld joints and vice versa. For achieving highest tensile strength, the best optimum spindle speed of 1400 rpm and the welding speed of 20 mm/min. There is no significant difference observed in tensile strength, with varying welding speed 16, 20, 25 mm/min for the 1400 rpm spindle speed, but for higher spindle speed 2000 rpm, it shows great difference. However, it implies that optimal process parameter significantly affect output parameter i.e. tensile strength.

![Figure 2. Tensile strength with varying spindle speed](image2.png)

Tensile fractured at weld zone is shown in figure 3. The microstructure of the tensile fracture specimens with maximum tensile strength were observed under Scanning Electron Microscopy in order to observe the mechanism responsible for it.

![Figure 3. Tensile Fractured specimen of highest tensile strength](image3.png)

Tensile fractured surfaces of the FSW joints were observed under SEM at high magnification to understand the fracture mechanism as shown in figure 4. From the figure it can be seen that the fracture mechanism in the mixing of these alloys consists of numerous spherical dimples. These
dimple rupture indicates that fracture occurred with degree of ductility. But the existence of the defect can always cause a stress concentration around the defect zone during the tension test. Cavaliere et al. [9] (2008) reported that this phenomenon results in a strain locality that is higher than the yield strength. This ductility behaviour is prone to the higher tensile strength.

Figure 4. SEM image of failure surface of the highest tensile strength specimen

Hardness profiles were measured at the nugget area of welds on the polished cross sections at two places one near to bottom and other near to top. Approximately spacing between the two indentations was 5 mm. It clearly seen that hardness values at top is higher than the bottom in all possible combinations. It is possibly because of the preheating of the surface during welding at the top part of plate and not for bottom part of the nugget area. Figure 5 shows graphical presentation on hardness value with respect to spindle speed and welding speed. Maximum hardness found at spindle speed of 1400 rpm and welding speed of 16 mm/min. Also noticed a negative influence by the increasing the welding speed. Hardness value goes diminishing for the higher spindle speed i.e. 2000 rpm compare to 1400. There is no change observed in between the hardness value by changing the welding speed at 2000 rpm spindle speed. For achieving maximum hardness value, the optimum spindle speed is 1400 rpm and welding speed is 16 mm/min. This combinations lead to a grain structures refinement, which contribute to the higher hardness [15]. The increase in hardness is attributed to the formation of fine grains and intermetallic in the stir zone due to pre-heating taking place during welding process.

Figure 5. Hardness with varying spindle speed
Based on the result of above results, further experiments were carried out by adding copper powder in the weld pool. Above result reveals that for achieving maximum ultimate tensile strength the process parameters are 1400 rpm spindle speed and 20 mm/min welding speed. And for attaining good hardness the process parameters are 1400 rpm spindle speed and 16 mm/min welding speed. Copper micro-particles were used for the synthesis of composites by friction stir process due to good solid solubility of copper in the aluminium. This solubility increases as the temperature increases. If the contents of alloying elements exceed the solid-solubility limit, inter-metallic compound phases are formed. More inter-metallic phases are formed in aluminium alloys because aluminium has high electro-negativity and being trivalent. As mentioned earlier the rise in temperature helps in the formation of inter-metallic compound. This rise in temperature is achieved by friction stir process by increasing the tool rotational speed. In this study copper particles might have reacted with the aluminium and formed the inter-metallic phases.

Table 2 shows the values of tensile strength and hardness at the optimum process parameters with and without copper powder.

| Spindle speed (rpm) | Welding speed (mm/min) | Ultimate tensile strength (MPa) | Hardness (HV) |
|---------------------|------------------------|--------------------------------|----------------|
|                     |                        | Without Cu powder | With Cu powder | Without Cu powder | With Cu powder |
| 1400                | 16                     | -                  | -              | 92              | 105            |
| 1400                | 20                     | 66.06              | 96.54          | -               | -              |

From table 2 it is clear that the tensile strength has increased by the addition of copper particles. Due to the presence of Cu particles and formation of the inter-metallic phases there may be a chance of reduction in grain size. Also, due to the thermal mismatch between the particles and matrix, the dislocation density increases. However, as the temperature increases during friction stir process it anneals the material at stir zone or nugget zone, which decreases the dislocation density. Thus the ultimate tensile strength increases with addition of copper particles. Also the tensile strength is higher due to high level of formation of inter-metallic phases. Homogeneous distribution of copper particles which is originated from Orowan strengthening mechanism prevents the grain boundary migration [16].

![Figure 6. XRD patterns of weld pool](image)

Figure 6 shows the XRD patterns of stir region. From the figure it can be seen that the peaks with square dots indicates the formation of inter-metallic compounds such as Al_{x}Cu. The peak with circular dot indicates the aluminium. The peak at 42 degrees shows the presence of copper.
From table 2 it is observed that micro-hardness has increased with the addition of copper powder. According to Orowan theory, when the rotational speed increases, more inter-metallic phases are formed. Inter-metallic phases formed caused effective precipitation hardening. Homogeneous distribution of copper particles in the stir zone or nugget zone eliminates the dislocations and improves the micro-hardness values.

4. Conclusions
This experimental study aims to investigate the effect of process parameters such as spindle speed and welding speed on the performance of friction stir weld joint and optimize these parameters for the better weld joint. From this experimental study following conclusions can be drawn.

i. From results, it is clearly observed that there is strong dependency of parameter spindle speed and welding speed on the performance of welded joints. There is different set of combination between the welding speed and spindle speed in order to get a maximum performance of weld joints.

ii. Optimum range of spindle speed, 1400 rpm and welding speed of, 20 mm/min was found for the maximum tensile strength (66.06 MPa), without addition of copper powder. Microstructure evaluations showed the formation of spherical dimple shaped new fine grains and refinement of reinforcement particle in the nugget zone (NZ). This leads to the more ductility and ultimately a possible explanation for the higher tensile strength.

iii. For achieving maximum hardness (92 HV) values spindle speed of 1400 rpm and welding speed of 20 mm/min were found to be optimal process parameters, without addition of process parameters.

iv. There was an improvement in tensile strength and hardness values at the optimal process parameters and with addition of copper particles. Tensile strength of 96.54 MPa and hardness value of 105 HV was obtained with the addition of copper particles.

v. Thus with the addition of copper particles tensile strength increased by 46.306 % and hardness has increased by 14.13 %.

vi. XRD patterns for the weld pool showed the presence of copper and inter-metallic compounds.

Al6061 and Al6082 finds applications in automobiles, aerospace, and metal forming industries that desire high plasticity as obtained through the friction stir process. The Al6061-Al6082-Cu composites may find the applications in the area where high surface hardness is required such as machine components that suffer from wear during the service and needs localized treatments.

5. References

[1] Mohammadi J, Behnamian Y, Mostafaei A, Gerlich AP. 2015, Tool geometry, rotation and travel speeds effects on the properties of dissimilar magnesium/aluminium friction stir welded lap joints. *Mater. Des.* 75 95-112.

[2] Adamowski J, Szkodo M, 2007, Friction Stir Welds (FSW) of aluminium alloy AW6082-T6. *J. Ach. Mater. Manuf. Engg.* 20 403-06.

[3] Trimble D, O’Donnell G E, Monaghan J, 2015, Characterisation of tool shape and rotational speed for increased speed during friction stir welding of AA2024-T3. *J. Manuf. Process.* 17 141-50.

[4] Cavaliere P, Santis A De, Panella F, Squillace A, 2009, Effect of welding parameters on mechanical and microstructural properties of dissimilar AA6082–AA2024 joints produced by friction stir welding. *Mater. Des.* 30 609-16.

[5] Zhang Q, Gong W, Liu W, 2015, Microstructure and mechanical properties of dissimilar Al–Cu joints by friction stir welding. *Trans. Nonferrous Met. Soc. China* 25 1779-86.

[6] Omar S S, Hengan O, Sun W, McCartney DG, 2015, A review of friction stir welding of aluminium matrix composites. *Mater. Des.* 86 61–71.
[7] Zhang F, Xuekuan S, Ziyong C, Zuoren N, 2015, Effect of welding parameters on microstructure and mechanical properties of friction stir welded joints of a super high strength Al–Zn–Mg–Cu aluminium alloy. Mater. Des. 67 483-91.

[8] Cavaliere P, Campanile G, Panella F, Squillace A, 2006, Effect of welding parameters on mechanical and microstructural properties of AA6056 joints produced by Friction Stir Welding. J. Mater. Process. Technol. 180 263-70.

[9] Cavaliere P, Squillace A, Panella F, 2008, Effect of welding parameters on mechanical and microstructural properties of AA6082 joints produced by friction stir welding. J. Mater. Process. Technol. 200 364-72.

[10] Rodriguez R I, Jordon J B, Allison P G, Rushing T, Garcia L, 2015, Microstructure and mechanical properties of dissimilar friction stir welding of 6061-to-7050 aluminium alloys. Mater. Des. 83 60-5.

[11] Guo J F, Chen H C, Sun C N, Bi G, Sun Z, Wei J, 2014, Friction stir welding of dissimilar materials between AA6061 and AA7075 Al alloys effects of process parameters, Mater. Des. 56 185-92.

[12] Ilangovan M, Boopathy, Rajendra S, Balasubramanian V, 2015, Effect of tool pin profile on microstructure and tensile properties of friction stir welded dissimilar AA 6061-AA 5086 aluminium alloy joints. Defence Technol. 11 174 -84.

[13] Sadeesh P, Venkatesh M K, Rajkumar V, Avinash P, Arivazhagan N, Devendranath K R, Narayanan S, 2014, Studies on friction stir welding of AA 2024 and AA 6061 dissimilar. Metals Procedia Engg. 75 145-149.

[14] Dawood I H, Kahtan M S, Azmi R, Uday B M, 2015, Effect of small tool pin profiles on microstructures and mechanical properties of 6061 aluminium alloy by friction stir welding. Trans. Nonferrous Met. Soc. China 25 2856-65.

[15] Wang H F, Wang J L, Zuo DW, Song WW, Xinglin D, 2014, Effect of friction stir welding on microstructure and wear properties of 7022 aluminium alloy, Indian J. Engg. Mater. Sci. 21 557-562.

[16] Zhang Z, Chen DL, 2006, Consideration of Orowan strengthening effect in particulate reinforced metal matrix nano composites: a model for predicting their yield strength. Scripta Mater. 54(7) 1321–6.