Friction stir lap joining of automotive aluminium alloy and carbon-fiber-reinforced plastic

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Abstract. Multi-material combination such as aluminium alloys and carbon-fiber-reinforced plastics (CFRP) are increasingly used in the aircraft and automobile industries to enhance strength-to-weight ratio of the respective parts and components. Various processes such as adhesive bonding, mechanical fasteners and laser beam joining were employed to join metal alloy and CFRP sheets. However, long processing time of adhesive bonding, extra weight induced by mechanical fasteners and high operating cost of the laser is major limitations of these processes. Therefore, friction stir welding is an alternative choice to overcome those limitations in joining of CFRP and aluminium alloys. In the present work, an attempt is undertaken to join AA5052 alloy and polyamide 66 CFRP sheets by friction stir lap joining technique using pinned and pin-less tools. The joint qualities are investigated extensively at different joining conditions using two different types of tools and surface ground aluminium sheets. The results show that pin-less tool and surface ground aluminium alloy can provide the suitable joint with maximum joint strength around 8 MPa.

1. Introduction

Carbon-fiber-reinforced plastics (CFRP) have characteristic of lightweight, high strength-to-weight ratio, excellent corrosion resistance and outstanding chemical and fatigue resistance [1-3]. As a result, multi-material joining of lightweight aluminium alloy to CFRP sheets has gained tremendous attention in automotive and aerospace industries to reduce the weight of the components and improve fuel efficiency [4,5]. However, hybrid joining of aluminium and CFRP is a bit difficult due to their widely different thermo-physical and chemical properties [5-7].

Various processes are attempted for dissimilar joining of plastic to aluminium alloy such as adhesive bonding [8], mechanical fasteners e.g. bolt and rivets [9], ultrasonic welding [10], laser beam based joining [3,4] and friction based joining [5,11-13]. Adhesive bonding needs long processing time for joining, hence this process is not suitable for mass production considering the present demand of high production [7]. Mechanical fasteners increase overall weight of the components and deteriorate mechanical strength of the joint owing to the development of stress concentration at the hole [8]. Another alternative is laser beam based joining process that can join various kinds of plastic and metals at high speed. However, high cost of laser unit is the main limitation of this process [4,5]. In friction stir joining process, generation of heat at the tool – metal interface subsequently melts plastic to join with the metal alloy. In addition to a small amount of deformation of the base metal is one of the leading advantages of this process. Therefore, friction stir welding (FSW) has become a prominent
choice to join CFRPs and metal alloys [5,7,10].

Ngatsuaka et al [5,13] used friction lap joining process for joining AA5052 alloy and polyamide 6 (PA6) carbon-fiber-reinforced plastic by pin-less tool. In this process, generated frictional heat at the tool-aluminium interface conducts from Al to the plastic and melts small region of plastic close to the interface. The joint is finally completed when melted plastic, in contact with Al under pressure, solidifies. The authors suggested that aluminium and CFRP sheets were joined together through the formation of the oxide layer at the interface. The authors further reported ground AA5052 alloy surface increased joint strength from 1.0 to 2.9 kN [5]. Liu et al [7] joined AA6061 alloy to MC Nylom-6 plastic using friction stir lap welding and found maximum joint strength around 8 MPa. Esteves et al [12] could improve joint strength in friction spot joining of AA6181 to CFRP sheets by increasing tool rotational speed as higher speed formed larger joining area. In contrast to friction spot joining processes, Jung et al [3] achieved maximum joint strength around 3 kN in joining of AA5052 alloy to PA6 CFRP sheets using continuous wave diode laser beam. Authors suggested that presence of oxide layer at the joint interface could form molecular level chemical bonding in between aluminium and melted CFRP sheets. The authors witnessed similar observation in laser beam joining of PA6 CFRP with zinc coated steel and stainless steel sheets [6,14]. In another study, Zhang et al [4] reported protrusion on aluminium surface could improve joint strength in laser beam joining of AA7050 alloy to CFRP sheets. The authors suggested protrusions acted as a locking material that produced tight bonding at the interface and increased joint strength to 39 MPa. The above studies provide significant insights in joining of aluminium to CFRP sheets by different processes. However, quantitative understanding of the influence of welding conditions on joint properties in friction stir joining of aluminium to CFRP sheets is scarce in the open literature.

Present work reports an experimental study in joining of AA5052 alloy to CFRP (polyamide 66) sheets using friction lap joining (FLJ) process. The primary emphasis is quantitative understanding of joint characteristics using pinned and pin-less tools. Further, the effect of ground aluminium surface on joint quality is investigated. The joint bead profiles and joint strength are examined and correlated with the processing conditions.

2. Experimental Investigation

AA5052 aluminium alloy and polyamide 66 (PA6.6) carbon-fiber-reinforced plastic (CFRP) sheets were joined in lap configuration with Al sheets placed on top of the CFRP sheets (figure 1). The thickness of the CFRP sheets was 1.5 mm, and aluminium sheets were 2.5 and 1.0 mm, respectively. A typical gantry type FSW machine (made by WINXEN) was employed to join the sample sheets using WC-12% CO made rotating pinned and pin-less tools. Table 1 shows the chemical composition and ultimate tensile strength (UTS) of the sheets. The shoulder diameter of both pinned and pin-less tools was 18 mm, and pin height and the root diameter of the pinned tool were 1.8 and 6 mm, respectively. Both tools were tilted at an angle of 2° with the vertical axis in the direction of linear travel. Friction stir tools were employed to generate frictional heat and apply pressure at the tool-metal interface simultaneously. The pressure induced by the tools was measured using load cell coupled with the FSW machine. The axial pressure induced by the tool was around 300 kgf. Further surface of aluminium alloy sheets was wet ground up to surface roughness (R_a) of around 3 μm to compare the joint properties with un-grind aluminium alloy sheets. First, 2.5 mm thick AA5052 alloy sheets were joined with 1.5 mm thick CFRP sheets using pinned tool. Next, pin-less tool was used to join 1 mm thick AA5052 alloy sheets and 1 mm thick Al alloy to 1.5 mm thick CFRP sheets, respectively. Aluminium sheets of 1 mm thicknesses were joined in lap configuration to obtain suitable joining conditions. The processing conditions of aluminium to CFRP joint, shown in table 2, were set after several trials on Al to Al sheets and Al to CFRP sheets to achieve continuous bead appearance under visual inspection.

The joint bead profiles and the respective dimensions were characterised along the transverse cross-section after polishing. The interface of the joint was examined using a Hitachi S-4800 scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS). The tensile strength of the
joint was measured on a Shimadzu EHF-EG200KN-40L universal tensile machine at a cross-head speed of 0.5 mm/min. Three tensile specimens were tested for each process condition to examine the variability in measured joint strengths.

![Figure 1. Schematic diagram of experimental set-up for joining of AA5052 alloy and PA6.6 CFRP sheets.](image)

**Figure 1.** Schematic diagram of experimental set-up for joining of AA5052 alloy and PA6.6 CFRP sheets.

**Table 1.** Chemical composition (in wt%) and ultimate tensile strength of workpiece materials.

|        | Mg  | Mn  | Zn  | Fe  | Si  | Cr  | Cu  | Ti  | Al   | UTS (MPa) | Thickness (mm) |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|------|----------|----------------|
| AA5052 | 2.5 | 0.1 | 0.1 | 0.4 | 0.25| 0.15| 0.1 | 0.15| Bal. | 252       | 1 and 2.5     |
| Polymer|     |     |     |     |     |     |     |     |      |           |                |
| Fiber  |     |     |     |     |     |     |     |     |      |           |                |
| Fabric |     |     |     |     |     |     |     |     |      |           |                |
| Melting|     |     |     |     |     |     |     |     |      |           |                |
| Temp   |     |     |     |     |     |     |     |     |      |           |                |
| CFRP   |     |     |     |     |     |     |     |     |      |           |                |
| PA6.6  |     |     |     |     |     |     |     |     |      | 785      | 1.5           |
| Carbon |     |     |     |     |     |     |     |     |      |           |                |
| Twill  |     |     |     |     |     |     |     |     |      |           |                |
| 2/2    |     |     |     |     |     |     |     |     |      |           |                |

**Table 2.** Process conditions used for joining of AA5052 alloy to CFRP sheets.

|                | Rotational speed (RPM) | Plunge depth (mm) | Travel speed (mm/s) | Surface roughness (μm) | Sheet thickness (mm) |
|----------------|------------------------|-------------------|---------------------|------------------------|----------------------|
| Pinned tool    | 400                    | 0.8, 0.9, 1.0     | 1.0                 | 0                      | Al 2.5, CFRP 1.5     |
| Pin-less tool  | 400                    | 0.2               | 0.6, 0.8, 1.0       | 0 and 0.3              | Al 1.0, CFRP 1.5     |

3. Results and discussion

3.1. Experimental bead profile

Figure 2 shows the bead profile in dissimilar joining of 2.5 mm thick AA5052 alloy to 1.5 mm thick CFRP sheets using pinned tool at different plunge depth of 0.8, 0.9 and 1.0 mm for constant rotational and travelling speed of 400 rpm and 1 mm/s, respectively. Figure 2 depicts continuous joint; however, tunnel defect appears on the upper surface of aluminium alloy. The width of the tunnel was increased with an increase of the plunge depth. All joints exhibited low strength and failed under the application of force by hand. This can be attributed as the lower CFRP material is hard, it is not easy for the tool pin to be inserted into the CFRP, which causes insufficient stirring and frictional heat generation between the upper Al alloy and the lower CFRP material. In order to solve this problem, it was aimed to compare and evaluate joint properties using pin-less tool which could increase the generation of frictional heat between upper and lower material.

In friction stir lap joining by pin-less tool, the aluminium sheet thickness was reduced from 2.5 to 1 mm to conduct sufficient amount of generated frictional heat from the tool-aluminium interface to the joint interface for making a suitable joint. Figure 3 shows bead profiles and corresponding bead cross-
sections of Al to Al joint at different joining speeds of 0.2 and 0.3 mm/s for constant tool rotational speed and plunge depth of 500 rpm and 0.3 mm, respectively. Figures 3(a) and 3(b) show smooth and continuous bead with improper plunging at the starting point. This happens because of inappropriate clamping. Figure 3(c) depicts the formation of a continuous bead at a travel speed of 0.3 mm/s; however, figure 3(d) shows a presence of small gap at the interface, indicating insufficient joint. This could be attributed to an increase in travel speed decreased heat input per unit length resulting in formation of gap at the interface. Therefore, travel speed of 0.2 mm/s is suitable for joining of Al to CFRP.

Figure 2. Bead profiles of Al and CFRP joint using pinned tool at different plunge depths of (a) 0.8, (b) 0.9 and (c) 1.0 mm for constant rotational and travel speed of 400 rpm and 1.0 mm/s, respectively.

Figure 3. Bead profiles and corresponding macrographs of Al to Al joint using pin-less tool at different travel speeds of (a, b) 0.2 and (c, d) 0.3 mm/s for constant rotational speed and plunge depth of 500 rpm and 0.3 mm, respectively.

Figure 4. Al to CFRP joint bead profile at a joining speed of 0.2 mm/s for rotational speed of 500 rpm and plunge depth of 0.3 mm.

Figure 4 shows bead profile of 1 mm thick AA5052 alloy to 1.5 mm thick CFRP sheets at a plunge depth of 0.3 mm for rotational and travel speed of 500 rpm and 0.2 mm/s, respectively. Figure 4 depicts rotational speed of 500 rpm causes deformation and warpage in the upper Al alloy sheet that
can be attributed to the low thermal conductivity of CFRP sheet, not conducting heat easily. As a result generated heat at the tool-workpiece interface is trapped in the aluminium surface and consequently distorts the aluminium sheet.

In order to control the heat input as mentioned above, the joints were made at higher travel speeds of 0.6 to 1.0 mm/s with lower rotational speed and plunge depth of 400 rpm and 0.2 mm, respectively. The bead profiles and cross-section of the bead for different travel speeds are shown in figure 5. Continuous joints were formed at high travel speeds with decrease in deformation of aluminium alloy sheets. Cross-section of the bead profiles for travel speeds of 0.6 and 0.8 mm/s could not be measured due to their breakage during cutting of the specimens. Cross-sectional macrograph of bead profile at joining speed of 1.0 mm/s, shown in figure 5(d), depicts bonding between Al alloy and CFRP sheets to some extent at the interface. This could be attributed to heat conducted from tool-aluminium interface partially melt CFRP sheet and consequently made a bond with aluminium alloy.

![Figure 5. Bead profiles and macrographs of Al to CFRP joint at a rotational speed of 400 rpm, plunge depth of 0.2 mm and different travel speeds of (a) 0.6, (b) 0.8 and (c,d) 1 mm/s.](image)

Further, surface roughness of $R_a$ 3 $\mu$m was prepared on the joining side of AA5052 sheet by wet grinding with emery paper to realise the influence of roughness on joint properties. Figure 6 shows bead profile and cross-section of joint at a rotational speed of 400 rpm, plunge depth of 0.2 mm and travel speed of 1 mm/s. Figure 6(a) shows continuous and smooth bead is formed with low distortion of aluminium sheets. Cross-sectional profile in figure 6(b) depicts frictional heat from top AA5052 surface partially melts CFRP near the joint interface and makes a continuous bond in between Al and CFRP sheet.

![Figure 6. Bead profile and cross-sectional macrograph of wet ground Al alloy and CFRP sheets at rotational speed of 400 rpm, plunge depth of 0.2 mm and travel speed of 1 mm/s.](image)

3.2. Characterization of joint interface

Figure 7 shows the scanning electron microscope image with results of EDS analysis at the interface of ground aluminium to CFRP joint for the rotational speed of 400 rpm and travelling speed of 1.0 mm/s. Figure 7(a) depicts aluminium alloy makes a strong bond with polyamide 66 near the joint
interface. This could be attributed to microgrooves in the ground aluminium surface filled with molten CFRP matrix led to form a tight bond in between Al alloy and CFRP sheets. Similar phenomena were reported earlier by several researchers for the joints of aluminium alloy to CFRP sheets [4,5]. The elemental concentrations across joint interface were examined further using energy dispersive X-Ray spectrometer (EDS) based point analysis. Figure 7 shows positions of EDS analysis at the joint interface and concentrations of Al, Mg and C elements at the interface. The EDS analysis was carried out at four points with two across the interface (points 5 and 6), one on the aluminium (point 3) and one on the CFRP surface (point 4). The concentration of different elements in Wt% at different points is shown in figure 7(b). The elemental concentrations of Al and C at points 5 and 6 confirm chemical bonding between aluminium and molten CFRP. It is, however, necessary to examine further the microstructural characteristics at the joint interface using TEM to get a deeper understanding of the bond between aluminium and CFRP.

![Figure 7. (a) Cross-sectional SEM image and locations of EDS analysis of ground Al alloy to CFRP joint, (b) elemental concentration of EDS analysis.](image)

3.3. Tensile shear strength

Figures 8(a) and 8(b) show the load-displacement and stress-strain curve of the joint between ground AA5052 alloy and CFRP sheets corresponding to the rotational and traverse speed of 400 rpm and 1.0 mm/s, respectively. The load-bearing capacity of the joint was measured in kN (figure 8(a)) and joint strength was estimated in MPa (figure 8(b)) as the ratio of the load and the original joint cross-section area. Figures 8(a) and 8(b) depict failure load and maximum joint strength respectively are around 2 kN and 7.6 MPa. Although all specimens were fractured at the joint interface, however, CFRP stick to the AA5052 was present on the fracture surface of the AA5052 sheet. The similar joint strength was achieved by Liu et al [7] in friction stir lap joining of AA6061 alloy to MC Nylon-6 plastic.

![Figure 8. (a) Load-displacement and (b) stress-strain curve of Al and CFRP joint at rotational and travel speed 400 rpm and 1.0 mm/s, respectively.](image)

| Point No | Al (Wt%) | Mg (Wt%) | C (Wt%) |
|----------|----------|----------|---------|
| Point 3  | 97.39    | 2.61     | 0       |
| Point 4  | 0        | 0        | 100     |
| Point 5  | 76.73    | 2.61     | 20.66   |
| Point 6  | 86.57    | 4.61     | 8.82    |
Figures 9(a) and 9(b) show fracture sample and scanning electron image of fracture aluminium surface. Presence of residual CFRP adhere to aluminium surface can be seen in figure 9(a). EDS area analysis was carried out further, and results showed the existence of significant elements were Al and C with a concentration of 36.18 and 63.82 Wt%, respectively. It could be confirmed that the fracture occurred along the joint surface but partially happened in between Al alloy and the CFRP base material. It is, however, necessary to improve the joint strength of aluminium to CFRP sheets. Alternative joining process such as friction spot joining (FSJ) could be employed further to investigate the joint properties of aluminium to CFRP sheets.

Figure 9. (a) Fracture sample and (b) SEM image of fracture sample at rotational speed of 400 rpm and travelling speed of 1.0 mm/s.

4. Conclusion
Following conclusions are derived from the present study:

- A detailed experimental study in friction lap joining of AA5052 to carbon-fiber-reinforced plastic sheets with pinned and pin-less tools are presented in the present work. Although reasonable joint strength is achieved, however, joining process parameters to get good joint is very restricted.
- Pinned tool exhibits tunnel defect and lower joint strength. That is because CFRP material is hard, it is not easy for the tool pin to be inserted into the CFRP, which causes insufficient stirring and frictional heat generation between the upper Al alloy and the lower CFRP sheet. On the other hand, pin-less tool produces continuous joints with reduction of deformation of Al alloy sheets.
- Maximum joint strength around 8 MPa is achieved in joining of ground Al to CFRP sheets using pin-less tool at a constant plunge depth of 0.2 mm for a rotational speed of 400 rpm and travel speed of 1 mm/s. Ground Al surface acts as locking material to interlock molten CFRP into Al alloy and leads to improve joint strength.

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