

Numerical modelling in friction lap joining of aluminium alloy and carbon-fiber-reinforced-plastic sheets

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Abstract. Multi-material combinations of aluminium alloy and carbon-fiber-reinforced-plastics (CFRP) have gained attention in automotive and aerospace industries to enhance fuel efficiency and strength-to-weight ratio of components. Various limitations of laser beam welding, adhesive bonding and mechanical fasteners make these processes inefficient to join metal and CFRP sheets. Friction lap joining is an alternative choice for the same. Comprehensive studies in friction lap joining of aluminium to CFRP sheets are essential and scarce in the literature. The present work reports a combined theoretical and experimental study in joining of AA5052 and CFRP sheets using friction lap joining process. A three-dimensional finite element based heat transfer model is developed to compute the temperature fields and thermal cycles. The computed results are validated extensively with the corresponding experimentally measured results.

1. Introduction

Lightweight materials of aluminium alloy and carbon-fiber-reinforced-plastic (CFRP) can significantly reduce the weight of the aerospace and automotive structures [1]. Various processes are attempted for joining aluminium and plastic with techniques such as adhesive bonding, mechanical fasteners, additive manufacturing, laser beam joining, ultrasonic spot welding and friction stir joining [1-6]. Adhesive bonding is not suitable due to its long time. Mechanical fasteners are used with relative success, however, high stress concentration close to the holes and additional weight of fasteners have been a problem. Another alternative is the laser beam welding process that has high operational cost [3]. Thus friction stir joining (FSW) has become a prominent choice due to its capability to join materials with low distortion.

Nagatsuka *et al* developed a method called friction lap joining process to join 3 mm thick AA5052 alloy and 2 mm thick polyamide (PA6) CFRP sheets [5]. Unlike FSW, a probe less cylindrical rotating tool is used in friction lap joining (FLJ) process to apply pressure to the metal surface and to generate heat at the tool/metal interface. The tool in FLJ process does not assist material flow like the probe tool performs in FSW process [5]. The generated heat at the tool/aluminium interface in FLJ process is conducted through aluminium alloy to the joint interface with an aim to partially melt the CFRP sheets and subsequently make a bond between metal and plastic after solidification of molten CFRP. The authors reported grinding on aluminium surface enhanced joint strength up to 60 MPa as the rough aluminium surface made a mechanical joint with CFRP sheets through anchoring effect [5]. In another study, authors found increasing Mg content in aluminium alloys improved the tensile strength of Al to CFRP joint [7]. In contrast to FSW process, Zhang *et al* reported maximum joint strength of around 39 MPa in laser beam joining of AA7050 alloy and PA6 CFRP sheets while Jung *et al* achieved joint



strength of approximately 30 MPa [1]. Although several studies examined the joint characteristic of aluminium to CFRP sheets in friction and laser beam joining processes. However, a quantitative characteristics understanding of the influence of welding conditions on the peak temperature, weld thermal cycle especially along the weld joint interface are rarely studied in friction lap joining of aluminium to CFRP.

In the present work, a combined theoretical and experimental study is reported in joining of AA5052 alloy and polyamide 66 (PA6.6) CFRP sheets in lap joint configuration using cylindrical tool assisted friction joining process. A three-dimensional finite element based heat transfer model is developed to compute the temperature fields and thermal cycles. The computed results are validated extensively with the corresponding experimentally measured results.

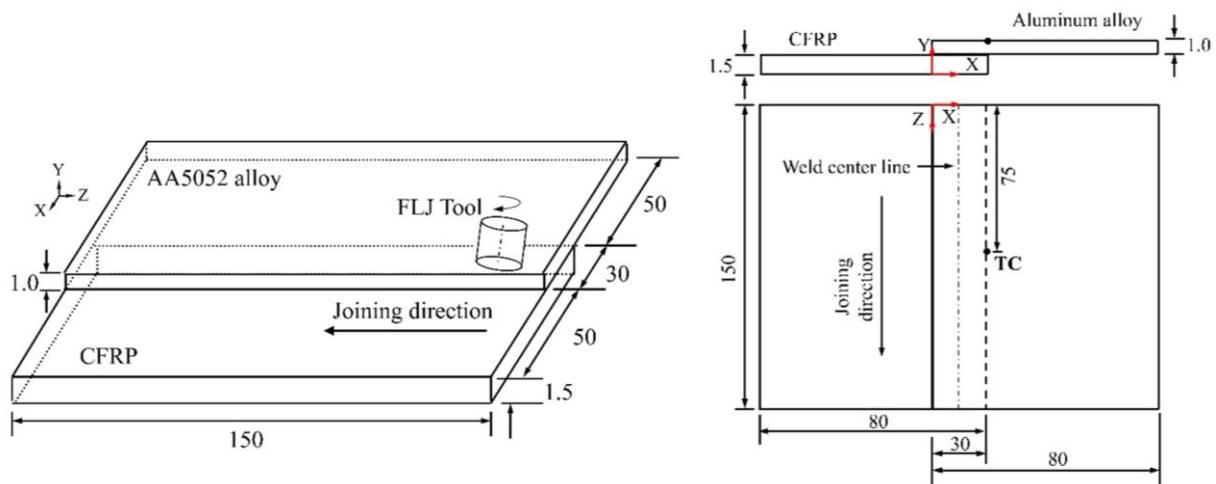


Figure 1. Schematic representations of specimen for friction lap joining of AA5052 alloy and CFRP sheets.

Table 1. Chemical composition of tool and workpiece materials in Wt% and joining conditions.

	Mg	Mn	Zn	Fe	Si	Cr	Cu	Ti	Al	Thickness
AA5052	2.5	0.1	0.1	0.4	0.25	0.15	0.1	0.15	Bal.	1 mm
	Polymer		Fiber	Fabric		Melting Temperature		Thickness		
CFRP	PA6.6		Carbon	Twill 2/2		533 K		1.5 mm		
Joining conditions	Rotational speed		Plunge depth	Joining speed (mm/s)		Surface roughness				
	400 rpm		0.2 mm	0.8 and 1.0		0.3 μm				

2. Experimental investigation

Figure 1 shows the schematic diagram of the dimensions of specimen. AA5052 alloy sheets of 1 mm thickness are joined with polyamide 66 (PA6.6) CFRP sheets in lap configuration by friction lap joining process. A gantry type computer numerical control operated friction stir welding machine (WINXEN made) is used in the present work. The tool is confirmed to WC-12% CO made with shoulder diameter of 18 mm and tilted at an angle of 2° with the vertical axis along the direction of joining. The aluminium surface, which is in direct contact with CFRP sheet, is ground to achieve surface roughness around 3 μm . Table 1 shows the details of work pieces and joining conditions. The joining conditions are chosen after performing several trial experiments to achieve continuous bead profile with no visible crack and distortion. The thermal cycles are measured during joining by K-type

thermocouple located at the top of aluminium sheets approximately at a distance of 30 mm from the aluminium edge as shown in figure 1. The weld dimensions are measured in transverse cross-section direction after polishing.

3. Theoretical formulation

A transient three-dimensional heat conduction analysis is developed to simulate friction lap joining process using the governing differential equation as [8]

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + \dot{Q} = \rho C \frac{\partial T}{\partial t} \quad (1)$$

where ρ , k and C refer to the density, thermal conductivity and specific heat, respectively; T and t refer to the temperature and time variables, respectively. The term \dot{Q} depicts internal heat generation per unit volume. The boundary condition is represented as [9]

$$k \left(\frac{\partial T}{\partial n} \right) - q_s + h(T - T_0) + \sigma \varepsilon (T^4 - T_0^4) = 0 \quad (2)$$

where n represents normal direction; h , σ and ε represent convective heat transfer coefficient, emissivity and Stephen-Boltzmann constant, respectively. The first term indicates heat loss due to conduction from the surface, the second term indicates applied heat flux on to the surface, and third and fourth terms indicate heat loss due to convection and radiation, respectively. The heat loss due to radiation is negligible in friction lap joining as the maximum temperature is below the melting temperature of the aluminium. A lumped heat transfer coefficient $h_0(T - T_0)^{0.25}$, where $h_0 = 70 \text{ W/m}^2\text{K}$, is used at the bottom of workpiece surfaces to account for the heat losses and a constant heat transfer coefficient of $20 \text{ W/m}^2\text{K}$ is applied rest of the surfaces.

The frictional heat (q_s) generated along the tool shoulder–workpiece contact area is computed analytically using equation (3) [9]

$$q_s = \eta_h \left[\eta_m (1 - \delta) \tau_y + \delta \mu_f P \right] \times (\omega r - U \sin \theta) \quad (3)$$

where η_m and η_h refer to fractional heat generated due to mechanical work of sticking friction and fraction of total heat goes in the workpiece, respectively. It is reported that the value of η_m for aluminium alloys is varying within the range of 0.2 – 0.6; in the present work, it is considered as 0.4 [9]. r depicts the radial distance from tool axis, and P , ω and U represent axial pressure, rotational and linear speeds of the tool, respectively. τ_y refers to temperature dependent shear yield strength of workpiece that is represented as $\tau_y = \sigma_y / 3^{1/2}$, where σ_y is the yield strength based on von Mises yield criteria. η_h is estimated considering one-dimensional steady state heat flow as [9]

$$\eta_h = \frac{\sqrt{(k\rho C)_{workpiece}}}{\sqrt{(k\rho C)_{workpiece}} + \sqrt{(k\rho C)_{tool}}} \quad (4)$$

The thermo-physical properties of the materials are shown in table 2. The terms, δ and μ_f represent the local variations in frictional sliding and coefficient of friction along the tool/ workpiece interface and are estimated as [9,10]

$$\delta = -0.026 + 0.5 \times \exp(r\omega/1.87) \quad (5)$$

$$\mu_f = 0.51 \times \exp(-\delta r\omega) \quad (6)$$

Table 2. Thermophysical properties of aluminium alloy and steel sheets.

Density, kg/m ³	AA5052: 2696.8 CFRP: 2136.7
Liquidus temperature, K	AA5052: 925 K CFRP: 533 K
Specific heat, J/ kg K	AA5052: $929.0 - 0.627T + 1.5 \times 10^{-3}T^2 + 4 \times 10^{-8}T^3$ CFRP: 1200
Thermal conductivity, W/ m K	AA5052: $25.2 + 0.398T + 7 \times 10^{-6}T^2 - 3 \times 10^{-7}T^3$ CFRP: 0.27278
Yield Strength, MPa	AA5052: $13.52 + 263.25 \times [1 + \exp\{(T-456.5)/29\}]^{-1}$

4. Result and discussion

4.1. Experimental bead profile

Figures 2(a) and 2(b) show top and bottom surface of the joint bead profile at a joining speed of 1 mm/s for a constant rotational speed of 400 rpm. Figure 2(a) shows smooth and continuous bead is formed with low distortion and little amount of flash on the aluminium surface. At the bottom side, shown in figure 2(b), small area of PA6.6 is melted (indicated by white block) by the frictional heat from aluminium surface and finally joined with aluminium alloy. A similar type of bead profile is reported by Nagatsuka *et al* [7] and Liu *et al* [11] in friction lap joining of aluminium and CFRP.

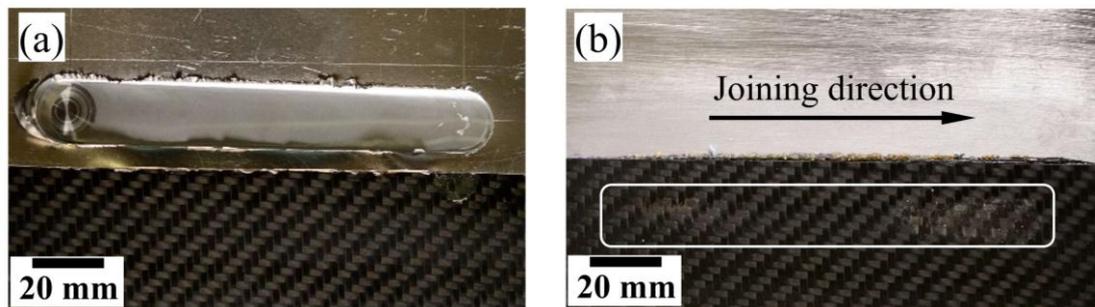


Figure 2. (a) Top and (b) the bottom surface of joint bead profiles prepared at a constant rotational speed of 400 rpm for joining speed of 1 mm/s. Melted portion of CFRP is represented by white block.

4.2. Thermal cycles

Figure 3 shows a comparison between the computed and the corresponding experimentally measured thermal cycles at the thermocouple monitoring location (figure 1) for two different joining speeds of 0.8 and 1.0 mm/s. The computed and the corresponding experimentally measured peak temperature are 474.2 and 486 K in figure 3(a), and 463.5 and 470.4 K in figure 3(b), respectively. A decrease in peak temperature in figures 3(a) and 3(b) is attributed to the reduction in heat generation per unit length of the joint with an increase in joining speed. Overall, a fair agreement between the computed and the corresponding measured thermal cycles is depicted in figure 3 that provides a premise to utilise the numerical model for a quantitative understanding of friction lap joining process to join aluminium alloys and PA6.6 CFRP sheets.

4.3. Computed temperature profiles

Figure 4 shows the computed temperature profile of transverse section in friction lap joining of aluminium to CFRP sheets for speeds of 0.8 and 1 mm/s. The position of the computed temperature profile is taken across the central axis of the tool. It can be noted that the workpieces undergo

maximum temperature region of 550 – 650 K, which is above the decomposition temperature of base matrix plastic and below the solidus temperature of the AA5052 alloy. The maximum temperature region in figures 4 indicates frictional heat generated at the tool/aluminium interface is sufficient to melt the CFRP sheet along the joint interface. A comparison of figures 4(a) and 4(b) shows the size of the maximum temperature region is decreased with increase in joining speed that can be attributed to the lower heat generation per unit length of the joint.

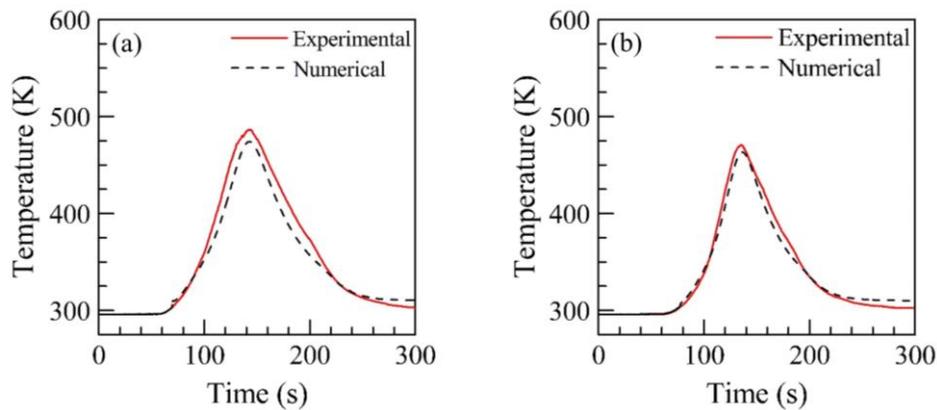


Figure 3. Comparison of numerically computed and corresponding experimentally measured thermal cycles at thermocouple monitoring locations at a constant rotational speed of 400 rpm for different joining speeds of (a) 0.8 and (b) 1.0 mm/s. The computed and measured peak temperatures (K) are: (a) (474.2, 486), (b) (463.5, 470.4).

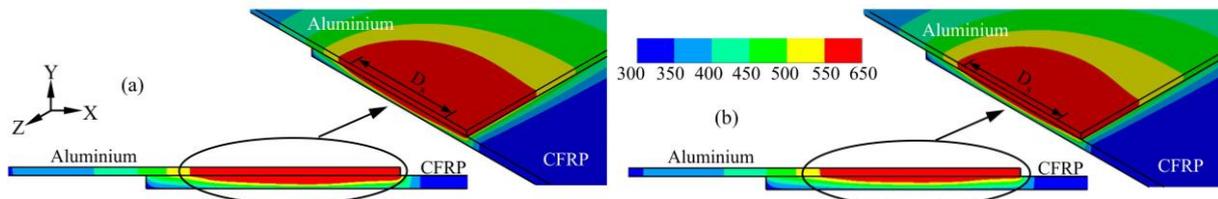


Figure 4. Computed temperature fields in friction lap joining of aluminium to CFRP sheets at a rotational speed of 400 rpm and at different joining speeds of (a) 0.8 and (b) 1 mm/s. D_s represents shoulder diameter and temperature in K is represented with colour band.

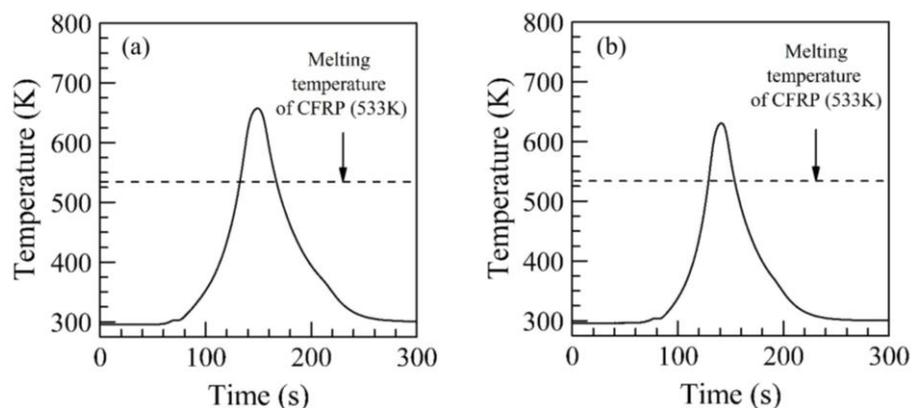


Figure 5. Computed thermal cycles at the joint interface in friction lap joining of aluminium to CFRP sheets at a rotational speed of 400 rpm and at joining speeds of (mm/s) (a) 0.8 (b) 1. The computed peak temperatures are (a) 657.7 K and (b) 625.5 K.

Further, numerically computed thermal cycles are evaluated at the joint interface where peak temperature is maximum. Figure 5(a) and 5(b) show the computed thermal cycles at the joint interface for joining speeds of 0.8 and 1 mm/s, respectively. The computed peak temperatures are 657.7 and 625.5 K, respectively in figure 5(a) and 5(b) which are above the decomposition temperature CFRP.

As a result, the friction lap joining process proves to be a useful technique where frictional heat generated at the tool/workpiece interface is transferred easily to decompose the CFRP sheets for making a bond with aluminium alloy. It is, however, necessary to examine further the microstructural characteristics especially extent of the formation of bubble along the joint interface, flow of molten plastic into the microgrooves of aluminium alloy and formation of oxide layer along the interface to understand the bonding mechanism between aluminium and CFRP.

5. Conclusion

An integrated theoretical and experimental study is reported on friction lap joining of automotive aluminium alloys and carbon-fiber-reinforced plastic sheets. A three-dimensional conduction based heat transfer model is developed considering heat generation due to friction and plastic deformation at the tool/workpiece interface. A fair agreement is achieved between the numerically computed and the corresponding experimentally measured weld thermal cycles. For the overall joining conditions considered in this study, the samples prepared are within a specific range of rotational and joining speeds have exhibited sound bead profiles without any visible discontinuity.

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