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Experimental Investigation on Thermal Properties of Al2024 Alloy by Friction Stir Welding

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Abstract: Friction stir welding (FSW) connects the parts without melting the metal and produces a plasticized zone of metal. The main objective of this paper is to examine the temperature distribution that results from friction stir-lap welding of Al2024 alloy at varying rotating speeds and feed rates. Temperature distribution, heat flow, directional heat flux, thermal stresses, and strain energy are analyzed at different speeds of 700, 1000rpm, and at feed rate of 20 mm/min and 40 mm/min. Comparing the experimental temperatures with the simulated temperatures an error of 0.6% has been observed which is negligible. By comparing the numerical values of heat flux to the simulated values, the maximum error found to be 5.8% for the similar lap Al 2024-T3 joint. Temperature and heat flux values are gradually decreased from nugget zone to thermo-mechanical zone. But when compared to the nugget zone with the thermo-mechanical zone, the values of thermal stress and strain energy were abnormally altered.

Keywords: Friction stir welding, AL2024 alloy, Temperature distribution, Heat flux, Thermal stress and strain energy

Introduction

Friction stir welding (FSW) is a solid state joining process that uses a third body tool to joining two facing surfaces. Heat is to be generated between the tool and material which leads to a very soft region near the FSW tool. It then mechanically inter mixes the two pieces of metal at the place of the joint, and then the softened metal can be joined using mechanical pressure, much like joining clay or dough. It is primarily used on aluminium and most often on extruded aluminium, and on structures which need superior weld strength without a post weld heat treatment.

For dissimilar lap joints, the temperature changes from low to high and vice versa at the 1000 rpm rotational speed which is lower than the melting point of the materials. This is mainly due to the two kinds of materials with different specific heat capacity, viscosity and thermal conductivity, and the mutual influence between temperature and material properties (Teng & Shen, 2016; Meng et al., 2021). High heat generation and low thermal gradient were obtained at an increased value of tool rotational speed which produced coarser microstructure in the HAZ (Song et al., 2014; Mahto et al., 2021). The lap shear strength generally increases

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with increasing welding speed (Dumpala et al., 2017; Paidar et al., 2020). These parameters can change the mechanical properties at the heat affected zone to thermo mechanically zone is to be studied.

Experimental Procedure

Experimental Analysis

Figure 1. Friction stir welding machine

Figure 1 shows the Friction Stir Welding (FSW) machine holding two Al2024-T3 alloy work pieces of size 125mm x 60mm x 6mm are used to be welded, by placing one over another and are clamped on a rigid back plate. The fixture prevents the work pieces from spreading apart or lifting during welding process. The welding tool, consisting of a shank, shoulder and pin is then rotated to a specified speed and oriented normal with respect to the work piece. During horizontal movement of spindle i.e., along Z- axis, welding was carried out with feeds of 20 & 40 mm/min for 125 mm length. The welding was done for two differentspeeds 700 and 1000 rpm. The temperature measured on tool, at welding and some distance from welding with infrared thermometer during welding process.

Numerical Analysis

The 3-D conduction equation is taken into consideration to determine the overall heat transfer during the welding process of comparable plates because heat transfer occurs between the rotating tool and the workpieces.The 3-D conduction equation is given by:

$$Q = -KA\left(\frac{dt}{dx} + \frac{dt}{dy} + \frac{dt}{dz}\right) \quad --\rightarrow (1)$$

Here,

Q = Heat Transfer in watts
K = Material's thermal conductivity = 121 W/m-K
A = Cross-sectional area = 15 x 10^{-3} m^2
t = Temperature distribution along X, Y & Z coordinates

$$dt = T_i - T_f$$

T_i = Initial temperature; T_f = Final temperature
dx = Change in length along X-axis = 45 X 10^{-3}m

Total heat flux,

$$q = \frac{Q}{A} \qquad --\rightarrow (2)$$

From the equations (1) and (2) we obtained the values as Q = 24259.92 W and q = 2.156 x 10^7 W/m^2 at a rotational speed of 700 rpm and feed of 70mm/min.

Modeling and Simulation Process

Transient thermal analysis was performed in the following two ways:

Geometry and Material Properties

Figure 2 shows the modeling of workpiece and tool geometry, which was done by selecting X-Y plane. A rectangle of size 45mm x 6mm was drawn by using sketching operation on drawing area and extruded to generate the rectangular plate to 125 mm length. Similarly, another rectangular plate is generated with the same dimensions. After modelling the workpieces and tool, Aluminium 2024-T3 alloy is assigned for workpiece (two plates) and H13 tool steel is assigned for tool.

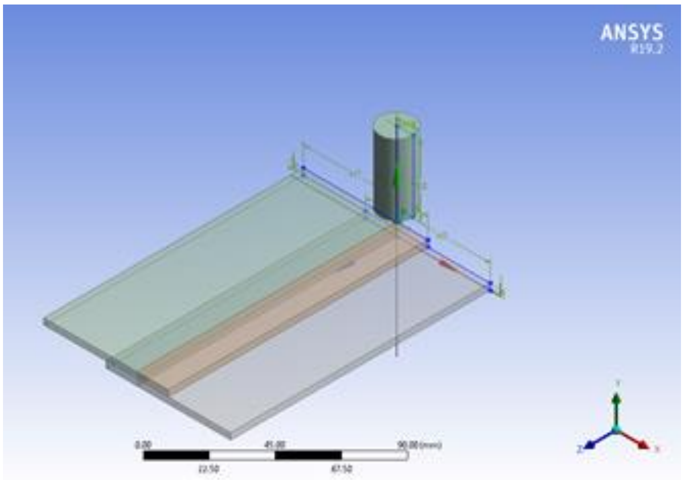

Figure 2. Creation of workpiece and tool geometry

Modeling and Solution

To update it, choose the mesh option and then choose fine size. Next, apply the generated temperature and initial temperature by clicking on Transient Thermal, and then click on Convection to apply the Film Coefficient to the surface.

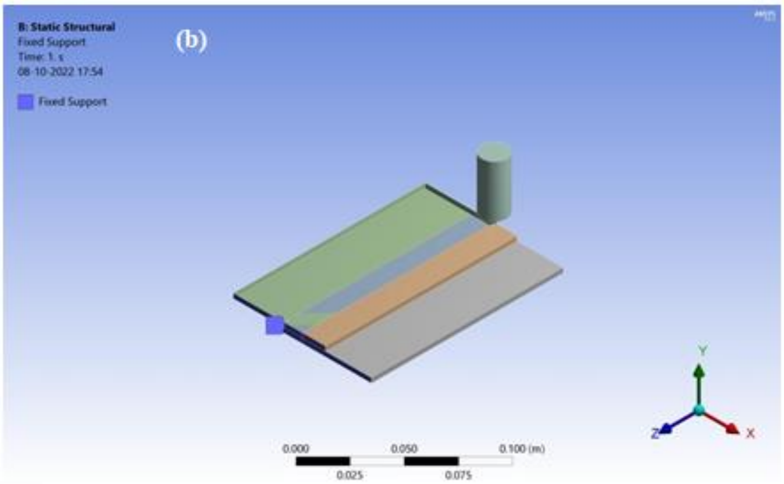

Figure 3. Boundary conditions applied to the developed model

Select temperature, heat flux, and directional heat flux in the solution phase before solving it. Select Static Structural once Transient Thermal is complete to connect the Model and Setup in Static Structural to the Geometry and Solution in Transient Thermal.To perform the static analysis, the rotational velocity of the tool was assigned and the boundary conditions were setup as shown in the Figure 3.

Results and Discussion

Experimentation Results

Table 1. Heat transfer at different spindle speeds for 2024-T3 similar lap joints

Spindle speed (rpm)	Feed Rate (mm/min)	Temp. (^{0}C)	Heat transfer (Watt)	Total Heat flux (W/m^2)
700	20	385	11524.62	1.283e7
700	40	396	14438.32	1.538e7
1000	20	408	15891.3	1.712e7
1000	40	436	16738.33	1.987e7

Similar plates made of Al2024-T3 are welded at spindle speeds of 700 and 1000 rpm with feed rates of 20 and 40 mm per minute. As stated in table 1, the maximum and minimum temperatures were determined. The temperatures and heat transmission through the material rise for similar joints as the rotating speed and feed rates increase. Additionally, as shown in table 1, the material's overall heat-flux increased.

Simulation Results

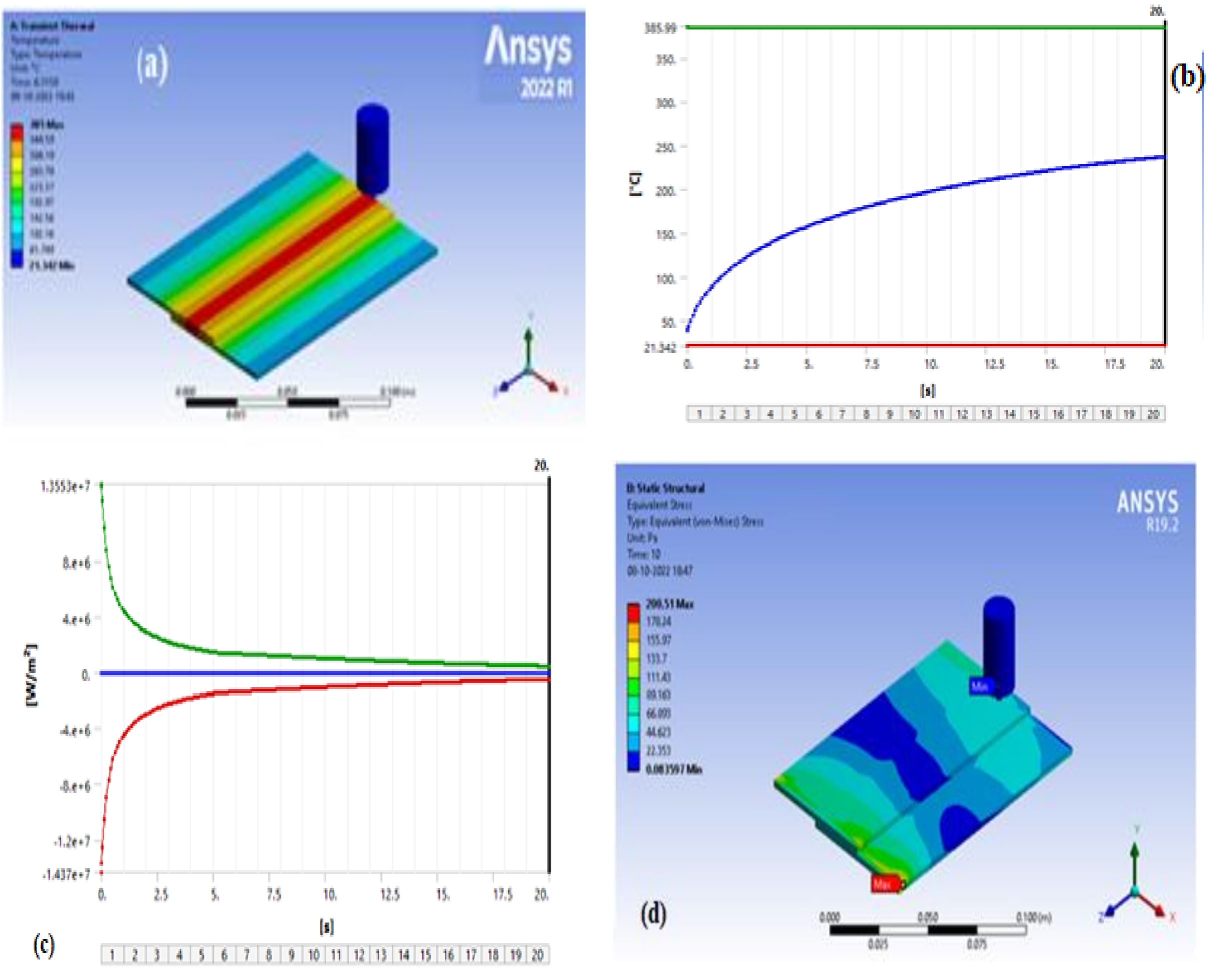

Figure 4. (a) Temperature distribution, (b) Graphical representation of maximum and minimum temperatures, (c) Graphical representation of directional heat flux, and (d) Thermal stress distributions.

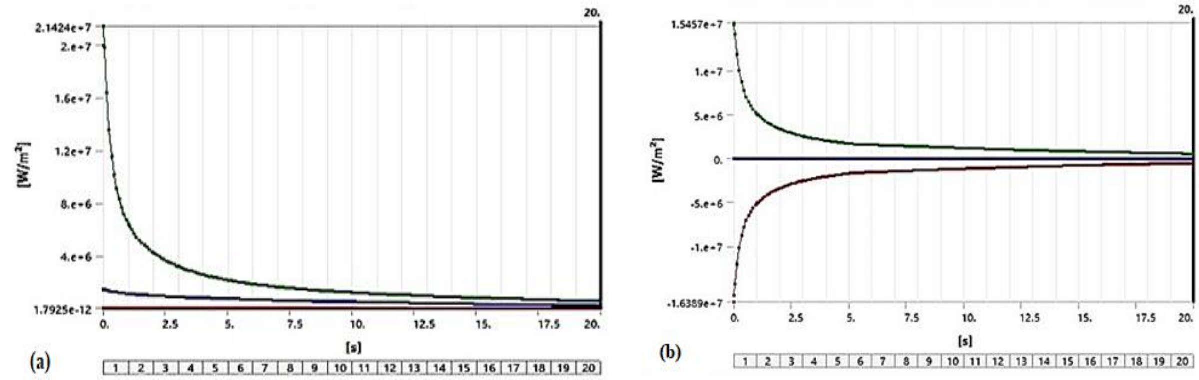

Figure 5. (a) Graphical representation of total heat flux, (b) Graphical representation of directional heat flux.

Figure 4 shows the results obtained for AA2024-T3 similar lap joint at spindle speed of 700 rpm and feed rate of 40 mm/min. The maximum temperature is 397.02°C and minimum temperature is 21.32°C whereas maximum directional heat flux is 1396.475 kW/m^2 and minimum directional heat flux is-1480.60 kW/m^2. Furthermore, maximum thermal stress is 577.34Pa and minimum thermal stress is 7.01 x 10^{-2} Pa. It was observed that the temperature, heat flux, thermal stress and strain energy are found maximum in the nugget zoneand are minimum at thermo-mechanical zone. Temperature and heat flux values are gradually decreased from nugget zone to thermo - mechanical zone. When compared to temperature and heat flux, the thermal stress and strain energy values are changing abnormally from the thermo-mechanical zone to the nugget zone.

Figure 5 shows the simulation results of AA2024-T3 similar lap joints at 1000 rpm rotational speed and feed rate of 40 mm/min. At spindle speed of 1000 rpm and feed tare of 40 mm/min, the maximum total heat flux of 2142.43kW/m^2 and minimum total heat flux of1.79 x 10-12 W/m^2, maximum directional heat flux of 1545.75kW/m^2 and minimum directional heat flux -1638.90 kW/$m^2$are obtained. It was found that maximum heat flux is obtained at the nugget zone and minimum value is obtained at the thermo-mechanical zone. These values are gradually decreased from nugget zone to thermo- mechanical zone. Temperature and heat flux values are gradually decreased from nugget zone to thermo-mechanical zone.

Comparison of Temperatures between Experimentation and Simulation

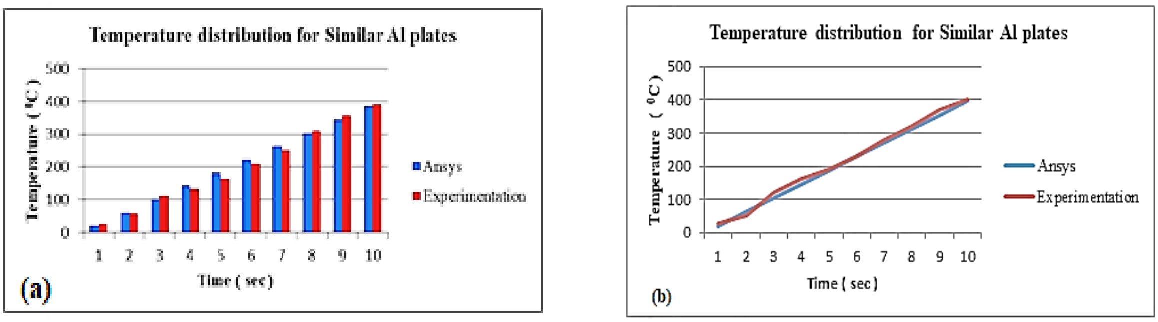

Figure 6: Comparison between the experimental and analytical values of temperature distribution (a) For spindle speed of 700 rpm with feed rate 20 mm/min, (b) For spindle speed of 700 rpm with feed rate 40 mm/min

From the figure 6, the error in temperature distribution between the experimental and analytical values is obtained as 0.25% for 2024-T3 similar lap joints. These results are well agreed with each other. From the above comparison graph it shows that the initial temperatures of all the weld joints are same but during the process the temperature will be increased.

Table 2. Percentage of error between the analytical and experimental valuesof heat flux

	Heatflux (W/m^2)		
S.No	Analytical	Experimental	% Error
1.	1.87 x 10^7	1.26 x 10^7	5.5
2.	1.93 x 10^7	1.58 x 10^7	3.8
3.	1.99 x 10^7	1.75 x 10^7	2.6
4.	2.14 x 10^7	1.93 x 10^7	1.9

From the table 2, it shows that the maximum error found for the similar 2024-T3 series is 5.5% at a rotational speed of 700rpm with a feed rate of 20mm/min. At a rotational speed of 1000 rpm with feed rate 40mm/min, the minimum error for 2024-T3 is 1.9%.

Summary and Conclusions

The major goal of this work to investigate the temperature distribution, heat flow direction, thermal stress, and strain energy at the weld bead of similar AA2024-T3 plates welded by Friction Stir Welding technique. This material is particularly used in the fields of transportation, military, marine, and aerospace.

- With spindle speed of 700 rpm and feed rate of 20 mm/min and 40 mm/min, it was found that maximum temperatures are 385.9^0C and 397.02^0C respectively. Total heat flux is 18785 kW/$m^2$and 19354 kW/m^2, directional heat flux is 13553 KW/m^2 and 13964 KW/m^2, thermal stress 200.51 Pa and 577.34 Pa, and strain energy 8.972 x 10^{-13}J and 7.44 x 10^{-12} J.
- With spindle speed of 1000 rpm and feed rate of 20 mm/min and 40 mm/min, it was found that maximum temperatures are 409.05^0C and 436^0Crespectively, Total heat flux is 19970 kW/m^2 and 21424 kW/m^2, directional heat flux is 14412 kW/m^2 and 15450 kW/m^2, thermal stress is 200.51 Pa and 577.34 Pa, and Strain energy is 8.979 x 10^{-13}J and 7.44x 10^{-12} J.
- By comparing the numerical heatflux data to the simulated values, it can be seen that the maximum error for comparable lap 2024-T3 joints was 5.5%, while the smallest error was 1.9%. This demonstrates that the materials' high thermal conductivity is highly heat dissipatedthat provides superior weldability.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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