Thermal prediction and experimental validation of Friction Stir Welded Aerospace Grade Aluminium Alloy

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Abstract. An integrated three-dimensional Friction Stir Welding (FSW) model with moving coordinate system is developed for aerospace grade aluminium alloy. Most of the previous researcher's work was based on the friction or stick and slip phenomenon with material modeling. In this present study, 3D heat transfer model is developed and integrated with both friction and stick-slip phenomenon using comsol multiphysics. The experiment was conducted on aerospace grade aluminium alloy 7075 with weld specimen size of 200mm X 100mm X 3mm. The temperature was recorded during welding with the help of high-temperature computerized data acquisition system (CDAQ 9212) in order to understand the thermal history of alloy at the pre-specified location. The recorded temperature values are validated with computed values. The measured temperature values at all thermocouple location in advancing side with error between 0.63 to 5.8 %, when compared with computed temperature.

1. Introduction

For the evolution of technology and industry, joining of materials has been long essential. Friction Stir Welding (FSW) was used as a solid-state joining process for welding similar and dissimilar aluminium alloys. Since 1991, friction welding and friction stir welding have become the hotspot to join lightweight materials such as aluminum alloy, magnesium alloy, copper and titanium alloys. Conventionally, in FSW generation of heat and heat transfer study is a fascinating and important aspect to understand the thermal cycles in weld specimen, hardness in stir zone, and material flow during welding and to calculate the weld quality [1]. During FSW, the heat generation was complex nature with high deformation behavior due to frictional heat between the faying surface and rotating tool. Due to this thermo-mechanical action, a suitable mathematical model with coupled comsol multiphysics solver necessary to predict thermal history [2]. From the equations of thermal heat transfer, a three dimensional FSW model was developed to analyze the influence of process parameters such as transverse speed of welding and tool rotating speed on heat transfer in the weld zone [3]–[7]. An axisymmetric 2D thermal model was built, and the model generated on multiphysics structural and thermal modules were used to plot the temperature curve [7]. The Eulerian based Computational Fluid Dynamics (CFD) model was built to simulate the material flow around the tool shoulder and pin of FSW setup to predict the material flow and to study the phenomenon such as slip & stick and flow velocity plot [8], [9]. A 3D fully coupled thermo-mechanical with incorporated tool material model was studied for a nearly small region between workpiece and tool, and the temperature dependent properties of the workpiece [10]–[14]. A three-dimensional finite element material flow and heat transfer model for Al5059 in a moving coordinate system was studied to understand the effects of
material temperature and tool speed on stir zone. The temperature at specific locations were computed in comsol multiphysics and validated with experimental values [12]. In case of the aerospace applications, FSW technique applied in the production of airframes, fuel tanks, and thin alloy skins. The present study was formulated to report the finite element with multiphysics model based on the approach of moving coordinate [1]. From the published literature the basic physics was heat generation and transfer due to thermo-mechanical action of tool pin and shoulder. The tool pin and shoulder initial produces the frictional effect on the faying surface which further leads to the severe deformation of material. Due to this action the material gets soften and tends to flow from advancing side to retreating side of the specimen. The involvement of complex multi-physics of heat generation, heat transfer, thermo-mechanical action and material flow in this study paves the way to develop an integrated 3D heat transfer model with stick-slip phenomenon using comsol multiphysics. It was observed that FSW process parameters highly influence the thermo-mechanical properties of aerospace grade aluminium alloy 7075. The thermal cycles at different zones of the welded specimen (AA7075) was computed numerically and validated through experiment.

2. Numerical Model

The numerical Multiphysics model couples a three-dimensional thermal analysis, for calculating heat flow, for two-dimensional axisymmetric swirl flow, for calculating both the flow and heat generation. Most importantly, the wide material database and specific modeling interfaces available in the heat transfer as well as tools for coupling variables from 2D and 3D modeling domains.

2.1. Modeling Approach

As mentioned by Song and Kovacevic [1] using the coordinate transformation, the heat transfer problem becomes a straight-forward stationary conduction-convection problem to the actual condition. The moving coordinate system moves the tool with respective to workpiece. While using moving coordinate transformation, it is not compulsory to model stir process of pin and shoulder. Further, the tool is taken as the origin point for the modeling and modeled with suitable tool material in that domain. Heat input in this welding process is achieved by three ways.

2.1.1 Pin to workpiece

The thermal model simulates the heat generation in the interface between the workpiece and the tool pin as a surface heat source [1,16]

\[ Q_{\text{pin}} = \text{if}(T<539[K],B,A) \]

\[ A = \frac{\mu}{\sqrt{3(1+\mu^2)}}(r_{\text{pin}}\omega)Y_{\text{bar}}(T[1/K])[\text{MPa}] \]

\[ B = \frac{\mu F_n}{A_{\text{ps}}}(r_{\text{pin}}\omega) \]

2.1.2 Shoulder to workpiece

The heat is generated at the interface between the tool shoulder and workpiece. The following expression describes the local heat flux per unit area (W/m²) at a distance 'r' from the center axis of the tool, source [1,16]

\[ Q_{\text{shoulder}} = \text{if}(T<539[K],B,A) \]

\[ R = \sqrt{x^2+y^2} \]

\[ A = \frac{\mu}{\sqrt{3(1+\mu^2)}}(R\omega)Y_{\text{bar}}(T[1/K])[\text{MPa}] \]

\[ B = \frac{\mu F_n}{A_s}(R\omega) \]
2.1.3 Stick-Slip phenomenon

Stick-slip phenomenon [16] is the cut off temperature at which complete sticking start. Complete sticking will start at the temperature at which \( \tau \) becomes equal to the shear strength. \( \tau \) will be equal to \( k (\mu P) \) when the value of \( k \) is less than \( \mu P \) (the maximum value of \( \tau \)). To find the temperature at which \( k \) becomes less than \( \mu P \), we must observe the variation of \( k \) with temperature. The value of \( \tau \) has been assumed to be zero at melting point, 908 K (as it takes negligible shear to deform a fluid). The other two values of \( k \) are legitimate lab test results. With the help of these results, the best fitting function is generated which gives the values of \( k \) as a function of temperature. The variation of \( \tau \) with temperature shown in Figure 1.

If the tool dimensions are assumed Shoulder Radius-6mm, Pin Radius-2mm, Pin Height-3mm and \( \mu P \) - pressure between the tool and the workpiece. This develops as a result of the downward force applied on the tool. In this study, the downward force (\( F \)) is assumed to be 5 kN [17]. In terms of the shoulder radius of the tool and the downward force applied the pressure between the tool and workpiece is \( P=F/A_s \). Based on this \( \mu P \), we can find out the cutoff temperature from the eqn. (8)

\[
T = -0.7624(\mu P) + 660.26
\]  

\( \mu P = 159.1549 \text{MPa} \)

The below equation describes the relation from which the temperature obtained for the corresponding value of \( \mu P \)

\[
T = -0.7624(\mu P) + 660.26
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**Table 1. Parameters for the stick-slip condition.**

| Notation                          | Values            |
|----------------------------------|-------------------|
| Force                            | 5kN               |
| Pin radius                       | 2mm               |
| Cross section area of the pin    | 12.56637mm^2      |
| \( \mu P \)                      | 159.1549MPa       |

The below equation describes the relation from which the temperature obtained for the corresponding value of \( \mu P \)

\[
T = -0.7624(\mu P) + 660.26
\]  

**Figure 1.** Variation of yield strength vs. temperature for AA7075.
Table 2. Parameters and input values used in this numerical model.

| Parameter       | Values        | Description                                      |
|-----------------|---------------|--------------------------------------------------|
| $T_0$           | 300           | Ambient Temperature in [K]                       |
| $T_{melt}$      | 908           | Workpiece melting temperature (K)                |
| $h_{upside}$    | 15            | Heat transfer coefficient, upside W/(m^2*K) [15]  |
| $h_{downside}$  | 1000          | Heat transfer coefficient, downside W/(m^2*K) [15]|
| $\epsilon$     | 0.3           | Surface emissivity for aluminium [16]            |
| $u_{weld}$      | 0.33, 0.5, 0.67, 0.83 | WS-Welding speed (mm/s)                     |
| $\mu$           | 0.4           | The friction coefficient of aluminium [16]       |
| $n$             | 900, 1000, 1100, 1200 | TRS- Tool Rotation speed (RPM)               |
| $\Omega$       | $2*\pi[\text{rad}]^n$ | Angular velocity (rad/s)                  |
| $F_n$           | 5             | AL-Axial force (kN) [17]                         |
| $r_{pin}$       | 2, 2.5        | PR-Pin radius (mm)                              |
| $r_{shoulder}$  | 6, 7.5, 8, 10 | SR-Shoulder radius (mm)                         |
| $A_s$           | $\pi*(r_{shoulder}^2-r_{pin}^2)$   | Shoulder surface area (mm^2)                    |

2.2. Meshing

Meshing used in this model is physics controlled mesh with extremely fine size option [10]. The mesh type tetrahedral is taken from the literature and most commonly used. The entire mesh contained 175496 elements with a minimum element quality of 0.01854 and an average element quality of 0.6945 shown in Figure 2.

Figure 2. Meshed model of AA7075. Figure 3. Boundary Conditions applied in AA7075 Plate.
2.3. Boundary Conditions

The heat transfer control equations are solved numerically with a finite difference method. In this study, the two plates to be welded are symmetric with the same material property. Instead of modeling two plates, only one plate is modeled with assumptions and heat transfer boundary condition made in this simulation as shown in Figure 3.

1. Initial Values - the whole system is considered to be at 300K [1].
2. Translational motion is a moving coordinate system that moves with the tool, instead of using a stationary system the translational velocity of the tool used as the input.
3. Insulation considered only for the similar welding simulation to avoid the heat loss in mid segment cross section.
4. Heat flux inward is nothing but the heat source from the shoulder to the workpiece.
5. Heat flux outward from all the surfaces with suitable heat transfer coefficient is considered from the literature [17].
6. Boundary heat source is boundary condition which defines the heat source from the cylindrical pin surface to the workpiece.
7. Radiation heat transfer includes the effect of radiation heat loss from the top surface of the workpiece.
8. Infinite domain assumes that the aluminium plates are infinitely long and neglects effects near the edges of the plate.

3. Experimental Studies

3.1 Material Properties

| Table 3. Chemical Composition of Aluminium Alloy 7075. |
|-------------------------------------------------------|
| **Composition in wt.%**                              |
| Al | Cr | Cu  | Mg  | Mn | Fe  | Si  | Ti  | Zn  |
| 87.1-91.4 | 0.18-0.28 | 1.2-2 | 2.1-2.9 | Max 0.3 | Max 0.5 | Max 0.4 | Max 0.2 | 5.1-6.1 |

3.2 Thermocouple Location

Figure 4. Thermocouple (TC) located in advancing and retreating side of welded plates.
The single-stranded insulated HSN 8544 k-type (chromel/alumel) thermocouple 30 SWG, 2 meters long with temperature range of -270 to 1260°C located at advancing side (TC1, TC2, TC3) and retreating side (TC4, TC5, TC6) at distance of 15mm, 20mm, 25mm from weld center at hole depth of 1.5mm, 2.0mm, 2.5mm from bottom surface with hole diameter of 2mm.

4. Results and Discussion

The numerical run designed with Taguchi L16 orthogonal array with five factors and four levels to minimize a large number of trails and corresponding peak temperature has been in table 4. From the numerical run, the optimized parameter with TRS-900rpm, WS-0.33mm/s, AL-5kN, SD-12mm, PD-4mm with the peak temperature of 691K is compared experimentally in below sections.

**Table 4. Numerical design matrix obtained from Taguchi L16 orthogonal array.**

| Numerical Run | A: TRS | B: WS | C: AL | D: SD | E: PD | Peak Temp.(K) |
|---------------|--------|-------|-------|-------|-------|---------------|
| 1             | 1100   | 0.33  | 7     | 20    | 5     | 844           |
| 2             | 900    | 0.67  | 7     | 16    | 4     | 774           |
| 3             | 900    | 0.50  | 6     | 15    | 5     | 762           |
| 4             | 1200   | 0.50  | 7     | 12    | 5     | 741           |
| 5             | 900    | 0.83  | 8     | 20    | 5     | 830           |
| 6             | 1100   | 0.50  | 8     | 16    | 4     | 797           |
| 7             | 1000   | 0.83  | 7     | 15    | 4     | 771           |
| 8             | 1100   | 0.67  | 5     | 15    | 5     | 787           |
| 9             | 1000   | 0.67  | 8     | 12    | 5     | 715           |
| 10            | 1200   | 0.83  | 5     | 16    | 5     | 812           |
| 11            | 1200   | 0.67  | 6     | 20    | 4     | 848           |
| 12            | 1200   | 0.33  | 8     | 15    | 4     | 791           |
| 13            | 900    | 0.33  | 5     | 12    | 4     | 691           |
| 14            | 1000   | 0.50  | 5     | 20    | 4     | 834           |
| 15            | 1000   | 0.33  | 6     | 16    | 5     | 791           |
| 16            | 1100   | 0.83  | 6     | 12    | 4     | 721           |

In this simulation, the tool direction is in X (+Ve direction) which can be clearly seen from the smaller size of Heat Affected Zone (HAZ) in front of the tool. The particular temperature distribution (Figure 5) is obtained when tool is in contact at mid-length of work piece. From the Figure 5, it shows the infinite domain is at ambient temperature of 300K which means that the region away from HAZ at
weld centres with minimum effect of welding speed (WS). It is also observed from the table 4, that the increment in the welding speed between 0.33 to 0.83 mm/s have less significance on peak temperature. The tool rotational speed is almost having direct impact on the peak temperature also leads to dynamic recrystallization in stir zone and very near to HAZ. The increase in tool rotation speed directly increases with deformation and the energy. This deformation energy is nothing but the shear stress deformation and it directly depend on the shear stress of the material [1] [15-17]. Further from the numerical trial, it is noted that the increase in pin diameter has less effect in peak temperature.

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The Figure 6. shows the computed temperature from simulation for numerical run 13 to the nodes at different cut plane 1.5mm, 2.0mm, 2.5mm from the bottom surface at distance of 15mm, 20mm and 25mm respectively from perpendicular direction to weld center. From simulation results, the peak temperature value of 691K obtained at the interface of tool pin and workpiece, which is practically impossible to measure. So the optimum thermocouple location has chosen near to the stir zone and verified experimentally. From the Figure 6. the temperature distribution at 2.0mm and 2.5mm cut planes are very closer than 1.5mm cut plane which clearly shows that the optimum range of depth in locating thermocouple is from mid plane thickness of plate. The numerical results are agreed with measured temperature with minimal error percentage of 0.63 to 5.8 through CDAQ system which is shown in the Figure 7. The trend line in Figure 6 & 7 shows that measured temperature value and computed temperature value are in good relation and found that there was slight difference in advancing side temperature to retreating side temperature [12]. Because of tool pin action and high strain rate in the advancing side softens material and flows to retreating side.

The advancing side temperature values alone are computed numerically and measured experimentally due to symmetric in size and shape. The Figure 8 validates numerical and experimental temperature at advancing side, the numerical value of 394.32 K at 25mm, 410 K at 20mm, 452.85 K at 15mm distance from weld centre is good agreement with the experimental value of 391.85K with % error of 0.63, 404 K with % error of 1.485, 428 K with % error of 5.806. Due to difficulty in locating thermocouple at the weld centre experimentally, the peak temperature value of 691K in stir zone has predicted only through developed 3D numerical model with the combined effect of friction and stick-slip phenomenon.
Figure 6. Computed temperature from simulated Model.

Figure 7. Measured temperature through CDAQ system.

Table 5. Validated temperature at advancing side for numerical run 13

| Distance from weld center in mm | 0  | 15 | 20  | 25  |
|--------------------------------|----|----|-----|-----|
| Numerical temperature in K     | 691| 452.85 | 410 | 394.32|
| Experimental temperature in K   | -  | 428 | 404 | 391.85|
| % Error                        | -  | 5.806 | 1.485 | 0.63 |
Figure 8. Validated numerical and experimental temperature at advancing side of welded plate.

5. Conclusion

In this present study, integrated three dimensional FSW model is built to analyze the temperature distributions of AA7075. Thermal values were predicted and compared with experimental results.

- The 3D integrated model was developed and analyzed with the combined effect of friction and stick-slip phenomenon using comsol multiphysics.
- With the help of integrated 3D model, maximum and minimum peak temperature value for aerospace grade AA7075 was predicated as 848 K and 691K respectively.
- In the advancing side, measured temperature value at thermocouple location TC3 as 428K at a distance of 15mm perpendicular to the weld center was in good agreement with numerically predicted temperature value of 452.85 K for same location.
- The temperature was recorded with the help of high-temperature computerized data acquisition system (CDAQ 9212) at the pre-specified location and validated with simulated results.
- The measured temperature values at all thermocouple location in advancing side (TC1, TC2, and TC3) with error % of 0.63 to 5.8, when compared with simulated values.
- From the above error percentage, it has been concluded that simulated values are in good agreement with the experimental values, which indicates that developed model was stabilized in consideration with the practical mechanism which happens in the real-time FSW process.

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