Temperature distribution in friction stir spot welding of aluminium alloy based on finite element analysis

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Abstract. Friction stir spot welding (FSSW) as the solid-state welding has been expanded to be used in various materials and many applications. The significant issue in FSSW is the existence of porosity or wormholes, leads to welding failure. One reason is due to imperfect heat generation leads to temperature distribution during FSSW effect to uncertain weldment formation. This is mainly influenced by improper parameters selection. In this study, the temperature distribution in the weld zones is investigated using finite element analysis via computer numerical simulation of Altair Hyperworks software with respect to parameters i.e. spindle speed, tool plunge depth, and tool dwell time. In the simulation, tool plunge depth and tool dwell time is set constant, but spindle speed was varied from 1400, 1500, and 1600 rpm respectively. Based on the results found that at a spindle speed of 1400 rpm was produced max temperature in the weld zone at 540 °C. Meanwhile, at 1500 rpm increased the temperature at 596 °C. At 1600 rpm reached its highest temperature at 650 °C. The results show that increasing tool rotational speed, at a constant tool plunge depth and constant tool dwell time will increase the amount of temperature distribution in the weld-zones. It is concluded that the suitable temperature distribution required in FSSW is 540 °C represented the solid-state joining process provided by spindle speed of 1400 rpm.

Keyword: Friction stir spot welding, finite element analysis, aluminium alloy

1. Introduction
The issue in manufacturing need a quick and accurate process to enhance quality of the products. Friction stir spot welding (FSSW) as a solid-state welding process has been broadly applied not only in manufacturing but also in many applications. FSSW is one of the welding technique used in Aluminium alloy as the variant of friction stir welding (FSW), developed by TWI in the UK in 1991 [1], offers advantageous moreover low distortion and low energy consumption that normally used to replace resistance spot welding (RSM) due to weld consistency, short electrode tip life, and welding defect e.g. porosity or void [2]. Basically, FSSW process affecting mainly by the spindle speed. The FSSW process generally composed of three significant actions i.e. plunging, stirring, and retracting as depicted in Figure 1. The plunging acts to move the FSSW tool reaches the workpiece until the tool
pin plunged into the predetermined depth in the workpiece. When the shoulder reaches the top surface of the workpiece, friction is expanded and heat is generated significantly. The generated heat was formed due to friction between rotating tool and workpiece, and severe plastic deformation in the workpiece \[2,3,4\]. Furthermore, the stirring allows the tool rotating at a certain time to form weldment \[4\]. Finally, the FSSW process is over through retracting the tool to the original position.

![Figure 1](image1.png)

**Figure 1.** The FSSW Process: (a) Plunging, (b) Stirring, and (c) Retracting \[6\].

2. Problem Identification
Understanding the process in FSSW, heat is generated via friction between the tool and work piece, yields plastic deformation caused by compressive loads of the tool. This forms modified microstructure around the joint \[6,7,8\]. As shown in Figure 2, there is no metallurgical modification in the base material (BM). In the heat-affected zone (HAZ), found modified the microstructure due to a thermal effect and plastic deformation. The moderate thermal effect including plastic deformation occurred in the thermo-mechanically affected zone (TMAZ). This is mainly followed by increasing the hardness in that zone \[10\]. The big change in microstructure can be seen in the stir zone (SZ) with fines microstructure with the highest level of the hardness.

![Figure 2](image2.png)

**Figure 2.** Zones in FSSW composed of the Stir Zone (SZ), Thermo-mechanically Affected Zone (TMAZ), Heat Affected Zone (HAZ) and Base Metal BM \[11\].

3. Finite Element Method
Employing FEA simulation in 2D or 3D model to describe temperature distribution inthe weld zones common in FSSW \[12\]. A study by Armansyah et al.\[13\] was done via 2D FEA-Model to plot a temperature distribution in FSWAA6061 influenced by spindle and travelling speeds during welding. The highest temperature of 460°C reached by using 600 rpm spindle speed and 4 sec/mm of travel speed. A study by Muhammed et al.\[14\] done via 3D non-linear FE model to explore the temperature distribution in FSSW of AA2024-T3 during FSSW. The distinct tool pin profiles of cylindrical, tapered and triangular are investigated at constant parameters. The 3D nonlinear heat transfer of the transient temperature field as a function with the time and spatial coordinates \((x, y, z)\) was used in the simulation. It was revealed, the highest temperature distribution was achieved by using cylindrical pin shape. This is believed due to high axial load and torque. It was seen that increasing the spindle speed, increased the heat generation in the weld zones with peak temperature of 315.9°C. It was about 50% of the melting point. Other study by Awang \[15\] successfully developed a 3D-FE model of FSSW process. The transient heat transfer was used in the simulation of thermal model.
4. Model Development
The 2D-FEA simulation was carried out via Altair Hyper-Xtrude solver including Hyper-Mesh solver. The workpiece material for FSSW specimen in the simulation was used Aluminium alloy 5052-H112 with 2 mm thick. The material for FSSW tool used in this study was steel with geometry and mechanical properties as tabulated in Table 1 and Table 2.

Setup the boundary condition of FSSW specimen in Hyper-Xtrude-Hyperworks software as shown in Figure 3. The 2D models then mesh with mesh type of quadrilateral as can be seen in Figure 4a, and boundary condition of FEM model of FSSW tool and workpiece specimen was exhibited in Figure 4b. Figure 5 shows the procedures in a flowchart of the process in FEA simulation of the temperature distribution in FSSW.

### Table 1. Work piece (AA5052) Material Properties

| Property                        | Value       |
|---------------------------------|-------------|
| Density (kg/m$^3$)              | 2680        |
| Specific heat capacity (j/kg.K) | 880         |
| Conductivity (W/m.K)            | 137         |
| Coefficient of Thermal expansion (1/K) | 1×10$^{-5}$ |
| Volumetric heat source (W/m$^3$) | 0           |
| Reference temperature (K)       | 700         |
| Liquidus Temperature (K)        | 922         |
| Solidus Temperature (K)         | 880         |
| Poisson ratio                   | 350×10$^{-1}$ |
| Modulus elasticity (Pa)         | 400×10$^{10}$ |

### Table 2. FSSW Tool Material Properties (Steel)

| Property                        | Value       |
|---------------------------------|-------------|
| Density (kg/m$^3$)              | 7870        |
| Specific heat capacity (j/kg.K) | 460         |
| Conductivity (W/m.K)            | 24.3        |
| Volumetric heat source (W/m$^3$) | 0           |
| Poisson ratio                   | 350×10$^{-1}$ |
| Modulus elasticity (Pa)         | 2.1×10$^{11}$ |

![Figure 3](image-url) Boundary Condition of FSSW tool and work piece in Software Hyperextrude-Hyperworks.
Figure 4. (a) FSSW tool and work piece FEM 2D Mesh; (b) FSSW tool and work piece Boundary condition of FEM model.

Figure 5. Flow chart of FEA simulation process.

5. Results and Discussion
In this part, the FEA simulations of temperature distributions are done. Figure 6 shows a temperature contour plot affected by the variation of spindle speed. The SZ was represented by red colour region which is the highest temperature distribution. The TMAZ, is handled by orange region, exhibits the moderate temperature distribution. Furthermore, the HAZ covered by yellow region, and the BM is in the green region.
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Figure 6. Countour plot of temperature distribution across the weld zones by using (a) spindle speed of 1400 rpm, (b) Spindle speed of 1500 rpm, and (c) Spindle speed of 1600 rpm.

The temperature distributions showed in Figure 6a affected by 1400 rpm spindle speed, reached the highest temperature in the SZ of 541 °C, 483 °C in TMAZ, 425 °C in HZ, and 367 °C in BM. Figure 6b shows the temperature distribution affected by 1500 rpm spindle speed, reached the highest
temperature in the SZ of 596 °C, 532 °C in TMAZ, 468 °C in HZ, and 3404 °C in BM. In Figure 6c, the temperature distribution by spindle speed of 1600 rpm, reached the highest temperature in the SZ of 596 °C, 532 °C in TMAZ, 468 °C in HZ, and 3404 °C in BM.

6. Conclusion
In this study temperature distribution across the weld zones are investigated according to the variation of spindle speeds of 1400, 1500, and 1600 rpm respectively. Aluminum alloy 5052-H112 was selected as the FSSW specimen and steel was chosen as the material for FSSW tool. The temperature distributions in the weld zones are investigated using finite element analysis via computer numerical simulation of Altair Hyperworks software. In the simulation, tool plunge depth and tool dwell time are set constant, but spindle speed was varied from 1400, 1500, and 1600 rpm respectively. Based on the results found that at a spindle speed of 1400 rpm was produced max temperature in the weld zone at 540 °C. Meanwhile, at 1500 rpm increased the temperature at 596 °C. At 1600 rpm reached its highest temperature at 650 °C. The results show that increasing tool rotational speed, at a constant tool plunge depth and constant tool dwell time will increase the amount of temperature distribution in the weld-zones. It is concluded that the suitable temperature distribution required in FSSW is 540 °C represented the solid-state joining process provided by spindle speed of 1400 rpm.

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