Simulation of Friction Stir Spot Welding of Copper and Aluminium During Plunging Phase

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Abstract. Simulation is limited and remains briefly addressed in the literature of friction stir spot welding (FSSW) process in joining dissimilar copper and aluminium. Thus, this study simulated the FSSW process of copper and aluminium to investigate the peak temperature during the plunging phase produced by all possible combinations of levels for tool rotational speed, plunge rate, and plunge depth according to the full factorial design. The modeling was established by Coupled Eulerian-Lagrangian (CEL) model and ‘dynamic, temperature-displacement, explicit’ analysis. The highest peak temperature of 994.4 oC was produced by 2400 rpm rotational speed, 100 mm/min plunge rate, and 1.6 mm plunge depth. The combination was suggested to be the optimum welding parameters in joining copper to aluminium as sufficient heat input was essential to soften the area around the welding tool and adequately plasticize the material. Three sets of confirmation tests presented consistent responses with a mean peak temperature of 994.4 oC, which validated that the response produced by the suggested optimum welding parameters was reliable. The statistical result reported that the variability in the factors could explain 84.12% of the variability in the response. However, only the rotational speed and plunge depth were statistically significant. The residual plots showed that the regression line model was valid.

1. Introduction
The Welding Institute (TWI) invented the friction stir welding (FSW) process in 1991 [1], which laid the foundation for the development of the friction stir spot welding (FSSW) process, solid-state welding [2]. Generally, there are three phases of the FSSW process where a welding tool plunges into the workpieces, stirs for a designated time, and draws out from the workpieces [2]. The plunging phase is particularly crucial because it creates the materials’ initial thermomechanical conditions [3]. The application of the FSSW process most commonly can be found in the automotive industry. The FSSW process makes it more convenient to join materials that are hard to deform, such as high tensile steel and aluminium casting. It also reduces running costs because riveting is no longer essential [4].

Meanwhile, common applications of copper (Cu) and aluminium (Al) can be found in the heat exchanger and automotive battery system [5, 6]. However, joining Cu to Al by the FSSW process is still uncommon in the industries. Therefore, simulation modeling may provide a safe and flexible environment for the industries to evaluate the feasibility of the FSSW process according to the industries’ standards before its full implementation. Coupled Eulerian-Lagrangian (CEL) model is suitable to simulate the FSSW process as it can simulate complex problems, especially when it involves large deformation [7].
2. Literature Review
Various experimental studies have been conducted to join Cu to Al (Cu-Al) or Al to Cu (Al-Cu) by the FSSW process to understand multiple aspects of the weld joint, especially in thermal analysis. Al-Sabur et al. concluded that the faster the tool rotational speed, the higher the heat generation [8]. Zhou et al. also reported the same result pattern where higher tool rotational speed produced higher heat input but lower torque and plunging force [9]. Meanwhile, Regensburg et al. found that increasing dwelling time or rotational speed of the tool increased the melt layer thickness produced by deformation- and friction-based heat input [10]. Besides, a previous study by Li et al. suggested that an increase in dwelling time encouraged the intermetallic layer’s growth as there was an increase in heat input during the welding process [11]. Cardillo et al. documented that different plunge depths did not change the peak temperature of the interface noticeably, though the plunge depth significantly affected lap shear strength [12]. Another study by Zhou et al. recorded that the threaded pin tool produced the highest peak temperature, resulting in the highest value of tensile shear failure load [13]. Although these studies on thermal analysis have been conducted experimentally, the study on simulation of Cu and Al by the FSSW process remains limited in the field.

3. Methodology

3.1 Materials and Design of Experiment
The base materials were aluminium AA1100 and copper C11000 plates with a thickness of 1 mm each. AA1100 has high resistance to corrosion and good formability, making it a safe choice for any chemical handling equipment. Meanwhile, C11000 is the most common electrical copper with high electrical conductivity. It is also known as electrolytic tough pitch copper, which has been refined electrolytically [14].

The simulation was designed based on the full factorial design, where it was composed of three levels and three controlled factors: tool rotational speed, plunge rate, and plunge depth, as per Table 1. Since there were three different plunge depths, welding tools with three different pin lengths were set up in the simulation. All H13 welding tools had the same 15.5 mm shoulder diameter and 4.5 mm pin diameter. However, the individual pin lengths were 0.9 mm, 1.2 mm, and 1.5 mm. Since they also shared the same 0.1 mm shoulder plunge depth, the total plunge depth became 1.0 mm, 1.3 mm, and 1.6 mm, respectively.

| Level | A Rotational Speed (rpm) | B Plunge Rate (mm/min) | C Plunge Depth (mm) |
|-------|--------------------------|------------------------|---------------------|
| 1     | 800                      | 50                     | 1.0                 |
| 2     | 1600                     | 100                    | 1.3                 |
| 3     | 2400                     | 150                    | 1.6                 |

3.2 Finite Element Modelling
ABAQUS software was utilized to simulate joining C11000 to AA1100 plates with 50 mm x 50 mm x 1 mm dimension for each plate. The plates were positioned in a lap configuration where C11000 was at the top and AA1100 was at the bottom. Since the actual FSSW process is generally quite complex to be
simulated, its complexity was simplified by assuming certain aspects. For example, the workpieces were isotropic and homogeneous, and the welding tools were isothermal rigid bodies. Meanwhile, the initial temperature of all nodes was pre-defined to 20°C, and convection and radiation were negligible.

The simulation demonstrated the FSSW process during the plunging phase with Coupled Eulerian-Lagrangian (CEL) as a model where both workpieces of C11000 and AA1100 were assigned to be 3D Eulerian parts. Meanwhile, the welding tools were set to a 3D deformable Lagrangian body but later established as an isothermal rigid body. ‘Dynamic, temperature-displacement, explicit’ analysis was selected in the step module. The respective angular tool rotational speed and plunge rate were assigned at the welding tool’s reference point. General, mechanical, and thermal properties were assigned accordingly to the respective parts as per Table 2.

### Table 2. General, mechanical, and thermal properties.

| Properties                | AA1100 [14] | C11000 [15, 16] |
|---------------------------|-------------|-----------------|
| Mass Density              | 2710 kg/m³  | 8190 kg/m³      |
| Young’s Modulus           | 69 GPa      | 117 GPa         |
| Poisson’s Ratio           | 0.33        | 0.34            |
| Expansion Coefficient     | 23.6x10⁻⁶ m/m.°C | 16.9x10⁻⁶ m/m.°C |
| Conductivity              | 222 W/m.°C  | 391.1 W/m.°C    |
| Specific Heat             | 904 J/kg.°C | 393.5 J/kg.°C   |

The contact interaction between parts was defined as general contact. The contact property was subjected to normal behavior and tangential behavior with a penalty friction formulation. In the simulation, the friction coefficient between surfaces was assumed to be 0.3 as Li et al. (2017) reported that it had the smallest relative error among the considered friction coefficients [17]. The plasticity model in the simulation was governed by the empirical law of Johnson-Cook where the symbol $\varepsilon$ signifies the equivalent plastic strain, the symbol $\dot{\varepsilon}$ represents the dimensionless plastic strain rate, and the symbol $T^*$ denotes the homologous temperature. Meanwhile, $A, B, n, C$ and $m$ are the material constants [18] as tabulated in Table 3. The equation can be written as:

$$
\sigma = [A + B \varepsilon^n][1 + C \ln \dot{\varepsilon}][1 - T^*m]
$$

### Table 3. Coefficients in the Johnson-Cook plasticity model.

| Constants | AA1100 [19] | Copper [18] |
|-----------|-------------|-------------|
| A         | 148 MPa     | 90 MPa      |
| B         | 361 MPa     | 292 MPa     |
| n         | 0.184       | 0.31        |
| C         | 0.001       | 0.025       |
| m         | 0.859       | 1.09        |

Uniform material assignment was created by choosing a region from the Eulerian domain and specifying its volume fraction using the Volume Fraction Tool (VFT). The volume fraction of 1 was set to C11000 at the top plate to indicate C11000 filled the upper Eulerian domain. The volume fraction of 1 was set to AA1100 at the bottom plate to indicate AA1100 filled the lower Eulerian domain. In the mesh module, the workpieces were set to the global size of 1 mm. The workpieces were assigned to the EC3D8RT element type, and the welding tool was assigned to the C3D8T element type. The meshed assembly of the parts is shown in Figure 1 below.
Figure 1. The meshing of the assembly.

4. Results and Discussions
The temperature distribution was available across the plates at the end of the plunging phase. The peak temperature was generated around the welding tool due to the frictional heat generation between the welding tool and the plates. Upon completing running simulations based on all possible combinations of welding parameters, the peak temperature results were tabulated in Table 4. The highest peak temperature of 994.4°C was produced by a 2400 rpm tool rotational speed, 100 mm/min plunge rate, and 1.6 mm plunge depth. The combination was suggested to be the optimum welding parameters because sufficient heat input was required to soften the area around the welding tool and adequately plasticize the material [2, 20].

Table 4. Peak temperature results.

| No | Notation | Rotational Speed (rpm) | Plunge Rate (mm/min) | Plunge Depth (mm) | Peak Temperature (°C) |
|----|----------|------------------------|----------------------|-------------------|-----------------------|
| 1  | 1 1 1 1  | 800                    | 50                   | 1.0               | 414.6                |
| 2  | 1 1 1 2  | 800                    | 50                   | 1.3               | 206.4                |
| 3  | 1 1 1 3  | 800                    | 50                   | 1.6               | 263.1                |
| 4  | 1 1 2 1  | 800                    | 100                  | 1.0               | 316.3                |
| 5  | 1 2 2 2  | 800                    | 100                  | 1.3               | 453.7                |
| 6  | 1 2 2 3  | 800                    | 100                  | 1.6               | 527.0                |
| 7  | 1 3 1 1  | 800                    | 150                  | 1.0               | 279.7                |
| 8  | 1 3 1 2  | 800                    | 150                  | 1.3               | 350.2                |
| 9  | 1 3 1 3  | 800                    | 150                  | 1.6               | 533.0                |
| 10 | 2 1 1 1  | 1600                   | 50                   | 1.0               | 644.8                |
| 11 | 2 1 1 2  | 1600                   | 50                   | 1.3               | 502.9                |
| 12 | 2 1 1 3  | 1600                   | 50                   | 1.6               | 591.8                |
| 13 | 2 2 1 1  | 1600                   | 100                  | 1.0               | 516.0                |
| 14 | 2 2 1 2  | 1600                   | 100                  | 1.3               | 688.0                |
| 15 | 2 2 1 3  | 1600                   | 100                  | 1.6               | 840.0                |
| 16 | 2 3 1 1  | 1600                   | 150                  | 1.0               | 452.4                |
| 17 | 2 3 1 2  | 1600                   | 150                  | 1.3               | 584.1                |
| 18 | 2 3 1 3  | 1600                   | 150                  | 1.6               | 754.4                |
| 19 | 3 1 1 1  | 2400                   | 50                   | 1.0               | 804.9                |
| 20 | 3 1 1 2  | 2400                   | 50                   | 1.3               | 695.2                |
| 21 | 3 1 1 3  | 2400                   | 50                   | 1.6               | 783.4                |
| 22 | 3 2 1 1  | 2400                   | 100                  | 1.0               | 655.5                |
| 23 | 3 2 1 2  | 2400                   | 100                  | 1.3               | 877.0                |
| 24 | 3 2 1 3  | 2400                   | 100                  | 1.6               | 994.4                |
| 25 | 3 3 1 1  | 2400                   | 150                  | 1.0               | 580.6                |
| 26 | 3 3 1 2  | 2400                   | 150                  | 1.3               | 718.0                |
| 27 | 3 3 1 3  | 2400                   | 150                  | 1.6               | 916.1                |
The simulation result was then followed by three sets of confirmation tests, as shown in Figure 2 to Figure 4, to verify the reliability of the response produced by the suggested optimum welding parameters. Table 5 showed that the peak temperature results were consistent, which gave out a mean of 994.4°C. Therefore, the confirmation tests validated that the response produced by the suggested optimum welding parameters in the FSSW process of the Cu-Al joint was reliable.

![Figure 2. First confirmation test (peak temperature = 994.4°C).](image)

![Figure 3. Second confirmation test (peak temperature = 994.4°C).](image)

![Figure 4. Third confirmation test (peak temperature = 994.5°C).](image)

**Table 5. Confirmation test results.**

| Confirmation Test | Peak Temperature (°C) |
|-------------------|-----------------------|
| First             | 994.4                 |
| Second            | 994.4                 |
| Third             | 994.5                 |
| Mean              | 994.4                 |

Afterward, the peak temperature responses were analyzed statistically by Minitab software to understand how the factors were related to the response. The model summary in Table 6 presented that...
the variability in the welding parameters can explain 84.12% of the variability in the peak temperature. The 84.12% R-sq value closer to 100% indicated a better fit than closer to 0%.

Meanwhile, Figure 5 showed that the main effects existed since different levels of welding parameters affected the peak temperature differently. Welding parameters of 2400 rpm tool rotational speed, 100 mm/min plunge rate, and 1.6 mm plunge depth were associated with the highest mean of peak temperature. However, the p-values in Table 7 suggested that only tool rotational speed and plunge depth were statistically significant because the tool rotational speed and plunge depth had p-values of 0.000 and 0.003, respectively, smaller than the significance level of 0.050. The Pareto chart of the standardized effect in Figure 6 presented that the bars that crossed the reference line of 2.086 were statistically significant, representing factors A, C, and BC. The blue bars represented terms in the model also showed that tool rotational speed had the largest effect on the peak temperature, followed by the plunge depth and, lastly, the plunge rate.

![Main Effects Plot for Peak Temperature](image)

**Figure 5.** Main effect plots for peak temperature.

**Table 6.** Model summary.

| S     | R-sq   | R-sq(adj) | R-sq(pred) |
|-------|--------|-----------|------------|
| 95.1836 | 84.12% | 79.36%    | 71.06%     |

**Table 7.** Analysis of Variance (ANOVA).

| Source          | DF | Adj SS   | Adj MS   | F-Value | P-Value |
|-----------------|----|----------|----------|---------|---------|
| Model           | 6  | 959904   | 159984   | 17.66   | 0.000   |
| Linear          | 6  | 959904   | 159984   | 17.66   | 0.000   |
| Rotational Speed| 2  | 764063   | 382032   | 42.17   | 0.000   |
| Plunge Rate     | 2  | 54838    | 27419    | 3.03    | 0.071   |
| Plunge Depth    | 2  | 141002   | 70501    | 7.78    | 0.003   |
| Error           | 20 | 181198   | 9060     |         |         |
| Total           | 26 | 1141102  |          |         |         |
Lastly, the validity of the regression line model was evaluated by the residual plots in Figure 7. The residuals without outliers in the normal probability plot (top left) were placed close to the diagonal line, representing the ideal normal distribution. The histogram (bottom left) showed that the data were normally distributed, not skewed, and had no outliers. Thus, the residuals satisfied the assumption that they had a normal distribution. Meanwhile, the points were random scattering above and below the reference line at horizontal 0 with no obvious patterns in versus fits plot (top right). The randomly scattered points suggested that the constant variance assumption was valid. In versus order plot (bottom right), the residuals were independent of one another as they fell in a random pattern around the reference line at 0. Therefore, the residual plots showed that the regression line model was valid as the residuals data was approximately linear, normally distributed, had constant variance, and independent as assumed.

5. Conclusion
The simulation reported that the highest peak temperature, 994.4°C, was produced by 2400 rpm tool rotational speed, 100 mm/min plunge rate, and 1.6 mm plunge depth. The combination was suggested to be the optimum welding parameters as softening the area around the welding tool and adequately
plasticizing the material required sufficient heat input to happen. The confirmation tests validated the reliability of the response produced by the suggested optimum welding parameters as the tests produced the peak temperature results steadily with a mean of 994.4°C. The statistical result presented that the variability in the welding parameters can explain 84.12% of the variability in the peak temperature. However, only the tool rotational speed and the plunge depth were statistically significant where the tool rotational speed had the largest effect on the peak temperature. The residual plots showed that the regression line model was a good fit for the data.

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Acknowledgments
The authors would like to acknowledge assistance from Digital Analytic for Structural Integrity Technology (DASIT) Research Group Universiti Teknologi PETRONAS (UTP) for providing licensed ABAQUS software.