The Effect of Friction Coefficient in Thermal Analysis of Friction Stir Welding (FSW)

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Abstract: The process of Friction Stir Welding (FSW) can be deeply investigated with the help of finite element modelling. In reality, the friction coefficient would decrease, because as the temperature rises the material becomes softer and weaker. However, past studies often presumed that the friction coefficient is a constant value, a presumption which consequently led to a disparity between the reality and the simulated model. This paper investigates the effect of applying temperature dependent and constant friction coefficient values to thermal behaviour during FSW. The comparisons between different models was done, and it was shown that the achieved temperature is affected by the friction coefficient. After comparing the results of models with results from experiments, it is concluded that the model in which temperature dependent values were applied is the most realistic one.

Keywords: Friction Stir Welding; Finite Element Modelling; Friction Coefficient; Thermal Analysis.

1. Introduction
There is a need to investigate the thermal behavior throughout the FSW as the welding temperature directly influences the welding quality and efficiency. A lot of research has proposed the thermal analysis of the process using finite element methods (FEM) [1-4].

In modelling the process, complex contact problems could be observed in the model, because of the presence of the friction phenomenon which is one of the most significant sources for the generation of heat. Thus, there is a need to precisely define the ratio between the friction force and the force holding two distinct bodies together. This ratio is named friction coefficient. The literature [5-8] in this field has employed some types of friction model which are constant. In this regard, past studies had estimated constant friction coefficient and documented values ranging from 0.3-0.5 [9-12]. These values were obtained by estimating the experimental measurement of the normal pressure and the tool torque [13, 14]. For instance, an alternative method was introduced by Schmidt and Hattel [8] which used a constant
friction coefficient and a full shoulder contact. They observed the presence of the sticking near the tool area and the presence of the slipping far from the tool. While the method is physically seemed realistic, however it was not feasible to get a single friction coefficient that can be used in every welding condition.

It should be mentioned that, some unsolved problems are still encountered in investigating the thermal history, temperature profile and temperature distribution throughout the FSW process. To illustrate, the influence of the slip rate, the friction coefficient, and the choice of the contact model have not yet extensively studied. As mentioned earlier, many researchers [15, 16] seldom considered the coefficient as a key factor and used constant values to define the contact condition because of the simplifications of models. In the meantime, the use of the constant friction coefficient value could lead to inaccuracy in the model specifically when there is large plastic deformation and high temperature in the model. Moreover, when there are high welding speeds in the model, the divergence problems would increase. Consequently, it is predicted that the discrepancy between the reality and the model would decrease and the convergence conditions would be achieved by calibrating of the contact input parameters. Therefore, this paper aims to study the influence of the friction coefficient in the FSW thermal behavior. Different values of the friction coefficient will be applied in the model, then the achieved temperature in each model will be compared with the results of experiments and the published papers in order to validate the FE model.

2. Methodology

2.1. Mathematical Model

The heat generation rate at the interface between the workpiece and the tool shoulder is a function of the geometry of the contact area, the workpiece interfaces and the tool shoulder [17]. Fundamentally, as the plastic formation increases due to the raise in temperature, it is expected that the friction coefficient will decrease [18]. So far, there is no straightforward method that can be used to estimate the frictional coefficient [19, 20].

Coulomb friction law expresses the shear stress at the interfaces as,

$$
\tau_{f\text{ric}} = \mu P_0
$$

Where $\tau_{f\text{ric}}$ represents the friction shear stress, $\mu$ represents the friction coefficient and $P_0$ presents the axial contact pressure [21]. As the temperature increases, the material behavior is dominated by von Mises shear stress criterion. According to von Mises theory, the shear stress ($\tau_y$) can calculated by [22],

$$
\tau_y = \frac{\sigma_y}{\sqrt{3}}
$$

Johnson-Cook material model (G. R. Johnson and H. Cook) can be used to prevent problems regarding plastic deformation and elastic-plastic mesh distortion [23].

$$
\sigma_y = [A + B(\varepsilon_p)^n] \left[ 1 + C \left( \frac{\varepsilon_p}{\varepsilon_p^0} \right) \right] \left[1 - \left( \frac{T_{FSW} - T_{room}}{T_{mel} - T_{room}} \right)^m \right]
$$

The parameters include welding temperature ($T_{FSW}$), room temperature ($T_{room}$), yield stress (A), strain factor (B), strain rate factor (C), strain exponent (n), material melting point ($T_{mel}$) and temperature exponent (m).

The value of the coefficient of friction is calculated as,

$$
\mu = \frac{\tau_0 - \tau_1}{(1 - \delta)P_0(1 - \sin \alpha)}
$$

Where $\delta$ represents the slip rate, $\tau_0$ shows the contact shear stress at the pin and the shoulder bottom surfaces and $\tau_1$ indicates the contact shear stress at the pin side area. It should be mentioned that, in the threaded cylindrical pin profile $\alpha$ presents the thread angle while in the conical pin profile $\alpha$ presents the angle of the cone.

The value of the slip rate will be achieved as below,
\[ \delta = \frac{\tau_1 - \tau_0 \sin \alpha}{(1 - \sin \alpha) \tau_y} \]  

(5)

Finally, the equation for measuring the friction coefficient values is written as follows,

\[ \mu = \frac{\tau_0 - \tau_1}{(1 - \frac{\tau_1 - \tau_0 \sin \alpha}{(1 - \sin \alpha) \tau_y}) P_0 (1 - \sin \alpha)} \]  

(6)

2.2. Numerical Model

The ABAQUS® was employed to model the FSW employing an Arbitrary-Lagrangian–Eulerian (ALE) formulation. The use of ALE prevents mesh regeneration and permits the free deformation of the mesh [5]. The stimulation used coupled temperature-displacement elements (C3D8RT) comprising of trilinear displacement and temperature, 8-nodes thermally coupled brick, reduced integration and hourglass control (number of nodes: 28357 and number of elements: 23832). Furthermore, elements of different sizes were applied to discretize the parts. The mesh located further from the welding seam are coarse mesh (2 mm) while those nearer to the welding zone are categorized as the fine mesh (0.8 mm). There are three steps defined for the simulation including plunging, welding and plunging out. Moreover, the probe will plunge until its shoulder touches the workpiece. It should be noted that, three different rotational speeds of 800, 1200 and 1600 RPM and three different travelling speeds of 40, 70 and 100 mm/min are applied in the model. Aluminum 6061-T6 was used for the workpiece material. Johnson cook material law was considered according to the literature [4]. The law states that the yield stress is a function of the strain rate and the temperature. Temperature dependent material properties and thermal coefficients are applied due to the literature [24, 25]. Figure 1. illustrates the FE model.

Figure 1. The Finite Element Model Dimensions and the Mesh

3. Results and Discussion

The contour plots for the model is shown in Figure 2. The calculated results showed that within the temperature range of 25 °C (room temperature) to 580 °C (material melting temperature), the friction coefficients for AA6061-T6 were in a range of 0.207089 to 0.000582 [26]. Table 1 presents the temperature results when the documented values (in the literature) and the measured values of the
friction coefficient are applied in the model. In this regard, the gap between the predicted temperature and the real temperature increased when the constant friction coefficient values are used. It should be mentioned that, the welding temperature in the plunging step should be less than the material melting point, because according to the literature the temperature will not exceed more than 80 to 90 percent of the material melting point during the FSW [27, 28].

![Figure 2. The Distribution of the Temperature in the Finite Element Model](image)

Table 1. The Percentage of the Error for the Temperature When Constant Friction Coefficient Values are Applied

| RPM, mm/min | Exp (ºC) | Temp COF 0.3 | Error (%) | Temp COF 0.4 | Error (%) | Temp COF 0.5 | Error (%) |
|------------|----------|-------------|-----------|-------------|-----------|-------------|-----------|
| 800,40     | 295.82   | 433.13      | 31.7      | 429.04      | 31        | 413.95      | 28.5      |
| 1200,40    | 304.59   | 432.45      | 29.5      | 384.99      | 20.8      | 448.47      | 32        |
| 1600,40    | 357.14   | 443.27      | 19.4      | 442.68      | 19.3      | 442.18      | 19.2      |
| 800,70     | 285.36   | 440.79      | 35.2      | 428.88      | 33.4      | 431.64      | 33.8      |
| 1200,70    | 295.82   | 447.30      | 33.8      | 423.47      | 30.1      | 430.91      | 31.3      |
| 1600,70    | 338.17   | 447.51      | 24.4      | 458.45      | 26.2      | 437.07      | 22.6      |
| 800,100    | 247.95   | 450.02      | 44.9      | 454.28      | 45.4      | 401.37      | 38.2      |
| 1200,100   | 296.55   | 443.29      | 33.1      | 407.69      | 27.2      | 430.42      | 31.1      |
| 1600,100   | 308.89   | 443.37      | 30.3      | 435.23      | 28.3      | 463.31      | 33.3      |

When the results of 0.3 coefficient compared to the experiments, the value of the temperature in the plunging step looks relatively realistic in transverse speeds of 40 and 70 mm/min and the rotational
speed of 800 RPM. On the other hand, the termination of the simulation makes this ratio unrealistic in other specimens. Furthermore, the maximum step time occurs in the second step (welding step, step time of 14.98 s) in two specimens with the transverse speed of 40 mm/min and the rotational speed of 1200 RPM and with the transverse speed of 100 mm/min and the rotational speed of 800 RPM. Therefore, almost all of the predicted values for the temperature do not agree with the experiments. The results showed that the best temperature prediction when the friction coefficient of 0.3 is applied in the model occurs in the rotational speed of 1600 RPM and the transverse speed of 40 mm/min where the gap between the results is approximately 86 °C and the absolute error is 19.4%. Furthermore, when the rotational speed is 800 RPM and the transverse speed is 100 mm/min the widest gap (203 °C) is happened (approximately about 203 °C with the absolute error of 44.9%).

When the friction coefficient of 0.4 is applied, for the plunging step it was apparent that except the transverse speed of 40 mm/min and the rotational speed of 800 RPM, the results of the plunging step are not precise and realistic. Moreover, the temperature at the transverse speed of 70 mm/min and 100 mm/min had about 12 °C and 34 °C differences with the real temperature, respectively. Meanwhile, when the rotational speeds of 1200 RPM and 1600 RPM are applied in the model, there is a considerable difference (around 80 °C to 100 °C) between the experimental results and the model in the plunging step. This illustrates that the role of friction coefficient is highlighted when higher rotational speeds are applied. This also shows that the discrepancy in the results is highly affected by the increase in the rotational speed.

Observations of the welding step also present that at the rotational speed of 800 RPM, the job could progress up until step time of 10 s, 11 s and 12 s with the absolute error of 31%, 33.4% and 45.4% approximately when the rotational speed is 800 RPM and the transverse speed is 40, 70 and 100 mm/min. Thus, according to the final predicted temperature, the rotational speed of 800 RPM and the transverse speed of 100 mm/min showed the biggest difference between the results (around 203 °C with the absolute error of 45.4%). It can be observed that the discrepancy of the results and the step time are highly affected by the transverse speed. Meanwhile, with the rotational speed of 1200 RPM, the step time was reduced, as the job was aborted in step time of 8 s with the absolute error of 31% (transverse speeds of 40 mm/min), 33.4% (40 mm/min) and 45.4% (40 mm/min). Moreover, during the rotational speed of 1600 RPM, the step time progressed until 10.5 s (40 mm/min) 9.3 s (70 mm/min) and 8.6 s (100, mm/min) with the absolute error percentage of 19.3%, 26.2% and 28.3% respectively. Consequently, the results of the step time illustrate an erratic pattern.

The results of the plunging step in the model with coefficient of 0.5 are deemed unacceptable. Moreover, the gap with the real temperature gradually increases as the rotational speed rise up. Similar to the results of the model with the coefficient of 0.3 and 0.4, at the rotational speed of 800 RPM and the transverse speed of 70 mm/min, the model with the coefficient of 0.5 showed the smallest temperature gap (about 37 °C). On the other hand, the rotational speed of 1200 RPM and the transverse speed of 70 mm/min showed the widest gap in the plunging step (approximately about 125 °C with the absolute error of 31.3%). This shows the importance of choosing the right friction coefficient at higher rotational and transverse speeds.

The welding step also shows unrealistic results similar to the plunging step. The rotational speed of 1600 RPM and the transverse speed of 40 mm/min showed the lowest temperature gap (approximately about 85 °C with the absolute error of 19.2%), while the widest gap (about 155 °C) was observed in the rotational speed of 1600 RPM and the transverse speed of 100 mm/min with the percentage error of 33.3%. The time step data showed that the rotational speed of 800 RPM and the transverse speed of 70 mm/min achieved the most successful run (about 9.32 s where the percentage of error is 33.8%), while the rotational speed of 1600 RPM and 70 mm/min was aborted in time step of 8.1 s where the absolute error is 22.6%.

Table 2 presents the temperature pattern when the calculated friction coefficient values are used in the model. It was observed that, the welding step temperature always exceeds to the real temperature in the plunging step and approximately there is a good parallel pattern between the numerical results and the experimental measurements obtained during the welding step. Moreover, the rotational speed of 1600
RPM and the transverse speed of 40 mm/min recorded the highest temperature (around 357 °C). In this light, it should be mentioned that in all models the job continued to the end of the plunging out steps for all specimens.

Table 2. The Final Percentage of the Error in Different Rotational (RPM) and Transverse (mm/min) Velocities

| Parameters (RPM-mm/min) | Experiment °C | FE model °C | Error % |
|-------------------------|---------------|-------------|---------|
| 800/40                  | 295.828       | 301.267     | 1.83    |
| 800/70                  | 285.366       | 287.57      | 0.77    |
| 800/100                 | 247.956       | 248.565     | 0.24    |
| 1200/40                 | 304.592       | 305.529     | 0.30    |
| 1200/70                 | 295.828       | 290.034     | 1.95    |
| 1200/100                | 296.551       | 288.301     | 2.78    |
| 1600/40                 | 357.146       | 365.044     | 2.21    |
| 1600/70                 | 338.173       | 344.461     | 1.85    |
| 1600/100                | 308.893       | 318.005     | 2.94    |

4. Conclusions
The use of the constant friction coefficient values leads to inaccuracy of the temperature results especially after the plunging step. Many researchers only model the plunging step, while others used constant values of the friction coefficient. This study compared the temperature dependent friction coefficient values and constant friction coefficient values in order to conduct the thermal analysis of the FSW process. FE model results showed that along with the increase in the rotational speed, the gap between the numerical results and experimental observations increased as the constant friction coefficient was increased from 0.3 to 0.5. Lastly, calculated friction coefficient values are deemed as fitting well for all welding temperatures and welding steps.

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