Heat Transfer Modelling of Friction Stir Lap Welding of PP Plastics and 6061 Aluminium Alloy

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Abstract—Structures with dissimilar materials can make full use of the advantages of each material. However the welding of the aluminum alloy plate and plastic plate are difficult due to high difference in melting point. The friction stir lap welding method is selected in this paper. The numerical model was built to study the heat transfer behavior inside the plates, as the temperature plays an important role in determine the weld quality. The model was validated through experimentally measured temperature results. The influence of welding process parameters such as welding speed, tool rotating speed and downward feed was analyzed. It was found that under the welding speed of 100r/min and downward feed of 0.3mm/s, sound weld was produced.

1. Introduction
Welding for aluminum alloys and thermoplastics is difficult due to the significant difference in material properties. Friction stir welding technology is a solid-state joining method, which uses heat generated by friction between the high-speed rotating welding tool and the workpiece to partially soften the welded material\textsuperscript{[1]}. The material is not melted during the welding process, hence it is suitable for welding dissimilar materials.

The study on welding of thermoplastics and aluminium alloy has been limited in the literature. Ren\textsuperscript{[2]} used friction stir welding to weld five common thermoplastics, PE, PC, PVC, PP, POM, and 1016 pure aluminum, 6061-T6 aluminum alloy. The influence of process parameters and welding speed on the weld formation was studied. The research results showed that PP is the most suitable plastic for friction stir welding, and the suitable order is PP> PC> PE> POM> PVC. Gok et al.\textsuperscript{[3]} based on the three-dimensional mesh re-split DEFORM model, studied the influence of various welding parameters on magnesium alloy friction stir welding. Based on the established three-dimensional friction stir welding finite element model, Buffa et al.\textsuperscript{[4]} studied the influence of the stirrer geometry and welding speed on the grain size and material flow of the weld nugget after welding, and improved the stirrer shape. Tang et al.\textsuperscript{[5]} performed the experimental temperature measurement and regular study of the field and found that any point on the material near the weld seam would experience a rapid temperature rise and slow temperature history. The maximum welding temperature was only 80% of the melting point of the material. In terms of modelling, both computational solid mechanics\textsuperscript{[6,7]} and
computational fluid dynamics methods have been managed to simulate the process.

The traditional friction stir welding can not be directly applied to the welding of thermoplastics and aluminium. The lap welding method without probe on the tool pin is adopted instead. However the numerical models for this welding method has been scarce. The temperature is key to the quality of the weld, affecting the microstructure and bonding strength. This paper proposes a model to simulate the temperature evolution.

2. Welding method
Welding test plate used 6061-T6 aluminum alloy plate and polypropylene pp plastic plate, and its size is 120*120*3mm. During the experiment, the 6061 aluminum alloy plate was lapped on the pp plastic plate, as shown in Figure 1. A hole with a diameter of 5 mm was punched in the designated position of the 6061 aluminum alloy plate to facilitate the overflow of the plastic on the surface of the pp plastic plate melted by heat during welding.

The welding parameters used in the temperature field simulation of this experiment are shown in Table 1. In this experiment, two temperature measurement methods were used for simultaneous temperature measurement: non-contact temperature measurement using infrared thermometer and thermocouples. The fluke tis65 9Hz infrared thermal imager was used for non-contact temperature measurement. The thermal imaging camera can record the temperature change process of the welded material at a resolution of 260x195 and a frame rate of 9 Hz.

| Type                        | Value   |
|-----------------------------|---------|
| Rotating speed (r/min)      | 1000    |
| Welding speed (mm/min)      | 100     |
| Welding inclination (°)     | 2       |
| Downward pressure depth (mm)| 0.3     |

Fig. 1 Illustration of friction stir lap welding of plastics and aluminium alloy

3. Numerical Modelling
The dimensions of the geometry are 120*120*3mm. Then select the extruded cut to punch the overflow hole at the specified location. The 3D brick solid element was selected for the FE model, as shown in figure 3. Three stages: preheating, welding and cooling were included in the model, a total of 6 analysis steps was defined in the model. Because the heat was only produced only by friction between the end face of the stirring tool and the material, the heat flux was assumed linearly distributed along the radius of the tool end face. The material properties were temperature dependent,
given in Table 2 and Table 3 for aluminium alloy and PP, respectively.

Table 2 Thermal properties of 6061

| Temperature (°C) | Density (kg/m³) | Thermal conductivity (W/(m*K)) | Heat specific (J/(kg*K)) |
|-----------------|-----------------|-------------------------------|-------------------------|
| 20              | 2680            | 176                           | /                       |
| 100             | 2680            | 180                           | 963                     |
| 200             | 2680            | 184                           | 1005                    |
| 300             | 2680            | 188                           | 1047                    |
| 400             | 2680            | 192                           | 1089                    |
By comparing the experimentally measured data and predicted results, shown in Figure 4 (a) and Figure 4 (b) for positions CH01 and CH04, respectively. The numerical model has been validated to simulate the temperature evolution.

| Temperature (°C) | Density (kg/m³) | Thermal conductivity (W/(m*K)) | Heat specific (J/(kg*K)) |
|------------------|-----------------|-------------------------------|--------------------------|
| 20               | 739             | 0.22                          | 1.74                     |
| 46.85            | 739             | 0.21                          | 1.78                     |
| 56               | 739             | 0.205                         | 1.82                     |
| 66               | 739             | 0.20                          | 1.88                     |
| 76               | 739             | 0.195                         | 1.96                     |
| 86               | 739             | 0.19                          | 2.07                     |
| 96               | 739             | 0.185                         | 2.24                     |
| 160              | 739             | 0.16                          | /                        |

Fig. 4 The comparison of measured and predicted results: (a) CH01, (b) CH04
4. Results
Weld preheating is the process of properly heating the local parts of the welded material prior to welding, the aim is to establish suitable temperature field for the start of the welding stage and reduce welding stresses and deformations. Weld preheating is an effective way to prevent welding cracks. The temperature contour plot was shown in Figure 5. It can be seen that the highest temperature was below the friction tool, both aluminium and PP materials have similar temperature distribution. The high temperature ensured the softening of the PP and forced the PP material flowing into the hole in the aluminium plate.

![Temperature contour plot](image)

Fig. 5 Temperature contour plot

The influence of FSW parameters can be found in Table 4. In the case of the welding speed unchanged, the peak temperature increased with the rotation speed and down feed of the stirring tool. When the speed of the stirring tool was constant, the peak temperature increased as the welding speed decreased and the downward feed increased. The downward feed has the greatest influence on the welding peak temperature, the tool rotation speed has a greater influence than the welding speed. The temperature evolution at the interface between aluminium plate and PP plate was given in Figure 6 for different welding speed and downward feed.

![Temperature evolution](image)

Fig. 6 The temperature evolution at the interface between aluminium plate and PP plate
Table 4 The peak temperature at different FSW parameters

| Rotating speed (r/min) | Welding speed (mm/min) | Downward feed (mm) | Peak Temperature (°C) |
|------------------------|------------------------|--------------------|-----------------------|
| 1000                   | 100                    | 0.3                | 362.7                 |
| 1200                   | 80                     | 0.3                | 301.8                 |
| 800                    | 100                    | 0.2                | 276.8                 |
| 1200                   | 100                    | 0.1                | 276.8                 |
| 800                    | 120                    | 0.3                | 330.8                 |
| 1000                   | 120                    | 0.1                | 250.4                 |
| 1200                   | 80                     | 0.2                | 317                   |
| 800                    | 80                     | 0.1                | 271.3                 |
| 1000                   | 80                     | 0.2                | 306.2                 |

5. Conclusion
The heat transfer model by finite element method was successfully established to investigate the heat transfer behavior during the friction stir lap welding process. The model was validated by experiment, good agreement between the measured predicted temperature.

The welding process parameter directly influenced the temperature evolution. The higher the tool rotation speed and downward feed, the higher the peak temperature. The faster the welding speed, the lower the peak temperature.

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