Numerical Simulation and Experimental Investigation of Friction Stir Rivet Welding Process for AA6061-T6

Peng Zhang¹, Shengdun Zhao¹, Wenwen Wang¹, Haixia Zhang¹, Jiaying Zhang¹, Changqun Yang², Yongfei Wang¹,³, Wei Wei⁴,⁵, and Guowei Ma⁴,⁵

¹School of Mechanical Engineering, Xi’an Jiaotong University, Xi’an, China
²Sinopec Marketing South China, Guangzhou, China
³State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou, China
⁴Oil and Gas Technology Research Institute Changqing Oilfield Branch Company of PetroChina Xi’an, Xi’an, China
⁵National Engineering Laboratory for Exploration and Development of Low-Permeability Oil & Gasfields Xi’an, Xi’an, China

Abstract. This article proposed a novel friction stir rivet welding process to join aluminum alloy 6061-T6 sheets in lap configuration with threaded rivet employed. The material flow behavior and temperature distribution of FSRW process are analysed using Simufact Forming 15.0 software, and joints have been obtained on the modified CNC machine with 1200rpm rotational speed and 10s dwell time. Rotational speed and dwell time are important factors which affecting mechanical properties of FSRWed joints. The welding heat input is determined by the rotation speed, while the heat time of plasticized materials is controlled by dwell time during FSRW process. In order to obtain FSRWed joints with excellent mechanical properties, welding heat input is taken as measurement standard, and the reasonable range of rotational speed and dwell time have been investigated by numerical simulation and statistics. The macroscopic morphology of 3 mm and 4 mm thick aluminum alloy 6061-T6 FSRWed joint we obtained shares uniform characteristic with the numerical simulation forming appearance whose upper surface tests smooth but exists “flash”, and stir zone, heat affected zone, thermo-mechanically affected zone and base metal four distinct zones can be observed in transverse section. The results of numerical simulation and experimental study show that the potential process we proposed takes advantages of solid-state welding and riveting technology. Not only metallurgical bonding can be obtained between upper and lower sheets, but also mechanical properties will be strengthened by riveting.

1 Introduction

Driven by the demands of lightweight mechanical equipment in the fields of aerospace, transportation, petroleum industry and so on, lightweight materials such as aluminum alloy
have been widely used to replace traditional steels. Therefore, high-performance connection of aluminum alloy has become an urgent problem.

At present, typical joining technologies of lightweight materials mainly include clinching, resistance spot welding and friction stir spot welding (FSSW) [1,2], clinching process could join the upper sheet and lower sheet together in lap configuration by forming a mechanical interlock between two sheets. Han [3] established the tensile strength prediction model, and optimized clinching process parameters through experimental verification and joint strength detection. Chen [4] significantly improved the tensile strength and shear strength of the connection point by adding rivets to the flat clinching joint. However, this process requires a large forming force, and the riveted joint shows low connection strength, poor tightness and appearance quality. Although FSSW process is permitted to join upper sheet and lower sheet together by metallurgical bonding, there exist keyhole defect which will weaken mechanical properties of the joint and limit its application in some structural parts [5]. Miles [6], Meschut [7], and EJOT [8] proposed a rivet plug welding (RPW) process to join dissimilar alloys (aluminum alloy to steel) by metallurgical bonding between rivet and lower sheet using high-speed rotation rivet through the upper sheet. However, much more heat input is needed to ensure metallurgical bonding strength between rivet and lower sheet for RPW process, what result in severe softening of aluminum alloy.

Friction stir rivet welding (FSRW) is a new process with potential for joining of aluminum alloy which takes advantages of solid-state welding and riveting technology. In this paper, numerical simulation of FSRW process in the form of lap joint is carried out for 3mm and 4mm thick 6061-T6 aluminum alloy (AA6061-T6) sheets using Simufact Forming 15.0 software, and joints have been obtained on the modified CNC machine with 1200rpm rotational speed and 10s dwell time. The effects of rotational speed and dwell time on temperature distribution is discussed and material flow behavior is analysed. In order to obtain FSRWed joints with excellent mechanical properties, welding heat input is taken as measurement standard, and the reasonable range of rotation speed and dwell time ranges we obtained can be used as a reference.

## 2 Materials and methods

### 2.1 Mechanism of friction stir rivet welding

The FSRW process principle is described in Figure 1 which mainly includes four steps: positioning, plunge and friction, dwell and retract. During FSRW, the rotating FSRW tool drives the positioned rivet plunge into workpiece which creates frictional heat between FSRW tool shoulder, rivet and surrounding material. Until FSRW tool shoulder enters in the upper sheet and reaches the preset plunge depth, the rotating motion of the rivet is stopped after dwell step. Finally, FSRW tool retracts to the coordinate origin and FSRWed joint can be obtained with plasticized material and rivet experienced natural cooling.

![Figure 1. Principle of FSRW process: (a) positioning step, (b) plunge and friction step, (c) dwell step and (d) retract step.](image-url)
2.2 Materials and numerical simulation setup

In this paper, the numerical simulation and experimental investigation of FSRW process in the form of lap joint are carried out for AA6061-T6 sheets with different dimensions of 45mm × 45mm × 3mm and 45mm × 45mm × 4mm, respectively. Simufact Forming 15.0 software is used for numerical simulation of FSRW process. Temperature (T) dependent properties of AA6061-T6 such as elastic modulus (E), yield stress (σ), poisson ratio (ν), thermal conductivity (λ) and specific heat capacity (c) are mainly set according to Simufact material database, which are shown in Table 1. Different sets of rotational speed and dwell time are contrasted to investigate material flow and influence mechanism of parameters on temperature distribution during FSRW process. In this numerical simulation, six different rotational speeds and dwell times are set as 800rpm to 1800rpm (200rpm interval) and 3s to 15s (2s interval) respectively. The feed rate of rivet and FSRW tool is 30mm/min, retract rate of FSRW tool is 60mm/min, and plunge depth of FSRW tool shoulder is 0.2mm.

<table>
<thead>
<tr>
<th>T/℃</th>
<th>E/GPa</th>
<th>σ/MPa</th>
<th>ν</th>
<th>λ/W·m⁻¹·K⁻¹</th>
<th>c/J·kg⁻¹·K⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>66.94</td>
<td>278.12</td>
<td>0.30</td>
<td>167</td>
<td>896</td>
</tr>
<tr>
<td>100</td>
<td>63.21</td>
<td>260.68</td>
<td>0.32</td>
<td>180</td>
<td>963</td>
</tr>
<tr>
<td>148</td>
<td>61.32</td>
<td>251.24</td>
<td>0.33</td>
<td>184</td>
<td>1004</td>
</tr>
<tr>
<td>204</td>
<td>56.80</td>
<td>221.01</td>
<td>0.33</td>
<td>192</td>
<td>1028</td>
</tr>
<tr>
<td>260</td>
<td>51.15</td>
<td>152.26</td>
<td>0.33</td>
<td>201</td>
<td>1052</td>
</tr>
<tr>
<td>315</td>
<td>47.17</td>
<td>73.87</td>
<td>0.36</td>
<td>207</td>
<td>1078</td>
</tr>
<tr>
<td>371</td>
<td>43.51</td>
<td>36.84</td>
<td>0.40</td>
<td>217</td>
<td>1104</td>
</tr>
<tr>
<td>426</td>
<td>28.77</td>
<td>21.58</td>
<td>0.41</td>
<td>223</td>
<td>1133</td>
</tr>
</tbody>
</table>

After numerical simulation, FSRWed joints are obtained at rotational speed of 1200rpm cooperate with 5s dwell time, and other parameters are consistent with the numerical simulation setup. Then, the macro-morphology of FSRWed joint transverse section observed under the optical microscope is compared with the temperature distribution obtained in numerical simulation.

3 Finite element modelling

3.1 Geometry description and mesh scheme

In this paper, 3D model of finite element (FE) model is established by SolidWorks software, as shown in Figure 2. Compared with AA6061-T6 sheet, the FSRW tool and rivet show much higher stiffness, they are considered as analytical rigid bodies in numerical simulation. In order to calculate feasibly and efficient, the geometric structures of FSRW tool shoulder and threaded rivet are simplified. The diameter of concave shoulder is 15mm, and the large/small end diameter of unthreaded conical rivet is 6mm and 4mm respectively with its height is 5mm. For two sheets in a lap configuration, two separate workpieces and remeshing means are employed for simulation. Mesh refinement is carried out in local cylinder area whose diameter is 16mm, and a total of 23332 advfront type elements have been generated in this model.
3.2 Boundary conditions setup

Heat sources mainly include plastic strain of workpieces and friction between FSRW tool shoulder, rivet and workpieces. In order to facilitate simulation, Coulomb friction model is used in this paper, and temperature dependent friction coefficients ($\mu$) of AA6061-T6 and steel are shown in Table 2.

<table>
<thead>
<tr>
<th>$T/\degree C$</th>
<th>22</th>
<th>34.7</th>
<th>93.3</th>
<th>147.5</th>
<th>210.6</th>
<th>260.0</th>
<th>315.6</th>
<th>371.1</th>
<th>426.7</th>
<th>582.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>0.61</td>
<td>0.545</td>
<td>0.259</td>
<td>0.115</td>
<td>0.064</td>
<td>0.047</td>
<td>0.035</td>
<td>0.02</td>
<td>0.007</td>
<td>0</td>
</tr>
</tbody>
</table>

Boundary conditions of our FE model are described as following: Initial temperatures for both workpieces, unthreaded rivet and FSRW tool were assumed at 25 $\degree C$; Convective heat transfer between upper surface and side of sheets, as well as convective heat transfer between bottom of lower sheet and backing plate were considered during FSRW process while thermal radiations were ignored; The convective heat transfer coefficients are 30W/(m$^2$·K) and 150W/(m$^2$·K), respectively.

4 Results and discussion

4.1 Thermal cycle and material flow

Material flow behavior and temperature distribution of FSRW process are similar to those of FSSW as shown in Figure 3, which are obtained at 1400rpm rotational speed and 5s dwell time. In the initial stage, materials of the upper sheet flow downward along the rivet plunge direction with speed about 0.2mm/s, and temperature around the rivet gradually rises to about 80$\degree C$. After 5s, some materials flow outward along the tangent direction of the rivet rotation axis with feeding of the rivet and aggravation of extrusion accompanied by friction. Material flow rates are 0.2mm/s~0.4mm/s while temperature of the rivet and surrounding materials reach 100$\degree C$~180$\degree C$. Once FSRW tool shoulder is plunged into upper sheet, a part materials are extruded to form flash while the other plasticized materials are stirred violently in the closed space between shoulder and rivet. After dwell stage, temperature of plasticized material rises sharply and peak temperature reaches 498.66$\degree C$ (about 86% of AA6061-T6 melting point), and the maximum material flow rate is 0.71mm/s. Temperature distribution consistent with the conclusions and experimental results obtained by many researchers [11,12], which shows that the numerical simulation model in this paper is reasonable and effective.
4.2 Effect of parameters on temperature change

Figure 4 shows thermal cycle curves around rivet at different rotational speeds. The laws of temperature change are basically the same at different rotational speeds while peak temperature increase respectively with speed increasing. The peak temperature is 346.76°C, when the rotational speed is 800 rpm. But it is 581.85°C has reached AA6061-T6 melting point at 1800rpm rotational speed which does not conform to the characteristics of solid phase bonding.

Dwell time is another important factor affecting temperature change. Figure 5 show the laws of peak temperature change at different rotational speeds with dwell time increasing. In dwell stage, the initial temperature under low-speed range (800rpm~1000rpm) is about 300°C and material plasticization in low degree whose friction coefficient is high to 0.04. In this case, the peak temperature amplitude (about 80°C) increases greatly with dwell time increasing. For middle-speed range (1200rpm~1400rpm), material plasticization degree is improved under the condition of 400°C initial temperature and friction coefficient decrease to less than 0.02. Once dwell time exceeds 10s, the peak temperature tends to stabilize. When rotational speed reaches high-speed range (1600rpm~1800rpm), the friction coefficient decrease nearly to zero at the initial temperature about 450°C, what cause the peak temperature appears slightly decrease under effects of convection heat transfer, material plasticization degree and riveting pressure though dwell time increasing.

Rotational speed and dwell time are important parameters that affect mechanical properties of the FSRWed joint. In order to control proper heat input and obtain FSRWed joint with excellent performance, reasonable rotational speed and dwell time should be chosen. Learning from FSSW process, FSRWed joint with excellent mechanical properties can be obtained without metallurgical defects such as pores and cracks only when heat input accounts for 70%~90% of the melting heat. In this research, we obtained the reasonable parameter ranges of rotational speed (1000rpm~1400rpm) and dwell time (3s~15s) for FSRW process.

4.3 Comparison of numerical simulation and experimental research

FSRWed joints for 3mm and 4mm thick AA6061-T6 sheets have been obtained on CNC machine with 1200rpm rotational speed and 10s dwell time, and threaded rivets whose thread parameter is M6x1 are employed in the welding process. Figure 6 compares temperature distribution and corresponding macro-morphology of the FSRWed joint. The
macro-morphology of upper surface shares uniform characteristic with numerical simulation forming appearance whose surface tests smooth but exists “flash”, as shown in Figure 6 (a). Due to microstructure distribution of the joint is highly dependent on temperature distribution during FSRW process, stir zone (SZ), heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and base metal (BM) four distinct zones can be observed in transverse section of the joint we obtained, as shown in Figure 6 (b). In summary, not only metallurgical bonding has been formed between upper and lower sheets, but also mechanical properties have been strengthened by riveting for FSRW process.

Figure 4. Thermal cycle curves around rivet at different rotating speeds.

Figure 5. Peak temperature at different dwell times.

Figure 6. Comparison of FSRWed joint macroscopic morphology and numerical simulation: (a) upper surface, and (b) transverse section.

5 Conclusion

In this study, the numerical simulation of material flow behavior and temperature distribution in FSRW process of AA6061-T6 sheets is performed, and the FSRW process with threaded rivet was employed has been successfully used to spot weld 3mm and 4mm thick AA6061-T6 sheets. The laws of temperature change are basically the same at different rotational speeds and dwell times while peak temperature increase respectively with speed and dwell time increasing. When rotational speed reaches high-speed range, the friction coefficient decrease nearly to zero at the initial temperature about 450°C in dwell stage, what still cause the peak temperature appears slightly decrease although dwell time increasing. The welding heat input is taken as a measurement standard, and the reasonable parameter ranges of rotational speed (1000rpm~1400rpm) and dwell time (3s~15s) we
studied in this research can be used as a reference to obtain FSRWed joint with excellent mechanical properties. Not only metallurgical bonding has been formed between upper and lower sheets, but also mechanical properties have been strengthened by riveting for FSRW process we introduced and investigated in this paper.

6 Acknowledgments

The authors gratefully acknowledge the National Natural Science Foundation of China for General Program (Grant No. 51675414), the Joint Funds of the Natural Science Foundation of Shaanxi Province (Grant No. 2019JLP-06), the Natural Science Basic Research Program of Shaanxi (Grant No. 2020JQ-067) and the Open Foundation of the State Key Laboratory of Fluid Power and Mechatronic Systems (Grant No. GZKF-201912), and reviewers' comments.

References