Application of Friction Stir Welding on the Large Aircraft Floor Structure

Wang Yisong, Tong Jianhua, Li Congqing
(China FSW Center, BAMTRI)

Abstract: As an innovative advanced joining technology for lightweight alloy, Friction Stir Welding Technology attracts more and more concerns and studies from manufacturing industries. As the leading field to adopt the most advanced technology, the aeronautic industry has focused on this technology for long time, and some optimistic outcomes have been obtained. In this paper, based on the typical FSW research and applications outcomes from international aeronautic industries, the floor structure on a large aircraft by friction stir welding technology was developed.

The material of the large floor structure is high-strength aluminum alloy 7050-T7451, and the length of the weld is 19m. It is not easy to weld the large-sizes and thin-walled structure by friction stir welding at the beginning; so many fundamental researches on mechanical test, shrinkage mass and so on were carried out. And laser tracking technology and constant force control technology during friction stir welding process were applied on this structure. The results indicate that the friction stir welding can be used on large-thin wall aircraft floor structure, which meet all the requirements of the aircraft floor structure design.

Key words: Friction stir welding(FSW); Floor; Welding shrinkage mass; Constant force control; Laser tracking; Clamp design

Friction stir welding is a solid plastic joining technology invented in 1991 by TWI. It uses a non-loss tool with special form, plugging in welded parts with the tool rotating, and then move forward along the interface between the welded parts. By stirring and friction, the materials to be welded is heated to the thermoplastic state, and the materials in the thermoplastic state transfer from front to back, meanwhile combined with the forging force from the tool, the welding seam forms. The schematic diagram of FSW is shown in figure 1.

The characteristics of Friction Stir Welding determine its unique advantage on low-melting alloy as aluminum, especially on 2XXX, 7XXX series high strength aluminum alloy, which are commonly used in aerospace structures and can’t be joined by fusion welding. This new joining technology provides more choices and possibilities on the applications of new materials and new
structure in the field of aircraft structure design. The friction stir welding technology’s application in high strength aluminum alloy aircraft structures gradually become effective approach on aircraft loss of weight, cost reduction, long-life design and manufacturing.

Figure 2 C-130, C-17 large transport aircraft FSW cargo work ramp and floor

Figure 3 Airbus body skin FSW process and real product

Figure 4 FSW Jet aircraft Eclipse-500

Over the past decade, the large-scale high strength aluminum alloy friction stir welding overall structures have been applied in several different military and civil aircrafts. Lockheed Martin has
applied friction stir welding in the C-130 floor fabrication. Boeing has also adopted friction stir welding on fabrication of the C-17 large transport aircraft cargo work ramp and floor, which was delivered to U.S. Air Force in June, 2005(as shown in figure 2). Airbus has applied its research findings of WAFS、TANGO international cooperation projects on large-scale aircraft body skin joining, which make it the first application of FSW on large-scale aircraft. Figure 3 shows the body skin FSW process, adopting vacuum adsorbing assemble clamp by Airbus, and the real product after assembly. The Eclipse adopted FSW on the Eclipse 500 business jet instead of riveting, including body skin, wing rib, chord supporting, aircraft floor and even the assembly of structures(as shown in figure 4). The European and American aviation field have developed the research on aircraft structure thick plate FSW. One of the typical application examples is FSW thick plate wing rib(as shown in figure 5), which save materials and reduce cost.

In summary, fabrication of FSW high strength aluminum alloy overall structure has become the development trend of the aircraft manufacturing technology. In this paper, aiming at fabrication of high strength aluminum alloy large-scale thin wall floor structure, many fundamental researches on weld joint mechanical property, shrinkage mass and so on were carried out. And force control technology and welding laser tracking technology were applied on the structure. The results indicate that FSW can realize the large-scale thin wall floor structure fabrication, which meet all the requirement of the aircraft floor structure design. And also it is one of the typical application examples in the field of FSW aircraft structure fabrication.

1 Experimental research on constant force control

Because the welding seam length of the floor structure is up to 19m, and the tensile strength of the weld joint is required to be no less than 90% that of base metal. Therefore, it’s a big challenge to ensure quality stability and uniformity of the welding seam. As to the conventional manual control, it’s difficult to ensure quality stability and uniformity of the welding seam and requires high level operator with much experience. While adopting the constant force control in the welding process, the automatic control of the welding process can be realized without manual interference, which can satisfy the requirement of quality stability and uniformity of the welding seam.

1.1 Experimental material and method
The experimental material is chosen as 3mm thickness 7050-T7451 aluminum alloy, and the
dimension of plane is 800×100×3mm. The welding experiments are carried out on the moving
gantry FSW machine with constant force control. The mechanical property tests are carried out on
Z100 electronic universal material testing machine. The optical microstructures are observed on
JENAPHOT2000 metallographic microscope. The chemical composition of the 7050-T7451
aluminum alloy is presented in table 1, and the mechanical properties of the base metal are shown in
table 2.

Table1 Chemical composition of 7050-T7451 (wt%)

<table>
<thead>
<tr>
<th>Mass percent/%</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloy</td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>≤0.12</td>
</tr>
<tr>
<td>Fe</td>
<td>≤0.15</td>
</tr>
<tr>
<td>Cu</td>
<td>2.0~2.6</td>
</tr>
<tr>
<td>Mn</td>
<td>≤0.10</td>
</tr>
<tr>
<td>Mg</td>
<td>1.9~2.6</td>
</tr>
<tr>
<td>Cr</td>
<td>≤0.04</td>
</tr>
<tr>
<td>Zr</td>
<td>0.08~0.15</td>
</tr>
<tr>
<td>Zn</td>
<td>5.7~6.7</td>
</tr>
<tr>
<td>Ti</td>
<td>≤0.06</td>
</tr>
<tr>
<td>Other</td>
<td>≤0.15</td>
</tr>
<tr>
<td>Al</td>
<td>Rest</td>
</tr>
</tbody>
</table>

Table2 Mechanical properties of 7050-T7451

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Supply state</th>
<th>Rm/MPa</th>
<th>Rp0.2/MPa</th>
<th>A/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>7050</td>
<td>T7451</td>
<td>495</td>
<td>425</td>
<td>9</td>
</tr>
</tbody>
</table>

During welding process, the speed of rotation is 700 rpm, the welding speed is 200 mm/min,
the tilt angle is 2.5°. The welding force changed from 6.5KN to 8.5 KN continuously. Within the
100mm length from the beginning, the welding force is a constant value of 6.5KN. And then, the
welding force increase 0.2KN once with each 70mm distance, till the welding force is up to 8.5KN.
The varying curve of welding force along the welding direction is shown as figure 6. The
mechanical properties test samples are cut out from different areas with different welding forces.
The varying curve of tensile strength with different welding force is obtained after mechanical
properties test.

![Figure6 The varying curve of welding force along the welding direction](image-url)
1.2 Experimental results and analysis

1.2.1 Influence of welding force on weld joint tensile strength

Figure 7 shows the varying curve of tensile strength with welding force. The results show that the tensile strength of 7050-T7451 weld joint increases with the increasing of welding force within the range of 6.5KN to 8.5KN at the same rotation speed, welding speed and tilt angle. And the tensile strength of weld joint exceed 90% that of base metal when the welding force exceed 7 KN. Considering the tensile strength of weld joint and the requirement of Heel Plunge Depth (≤0.2mm), the welding force of 7.7KN is selected as 7050-T7451 floor structure FSW welding force.

<table>
<thead>
<tr>
<th>Welding force (KN)</th>
<th>Heel Plunge Depth (mm)</th>
<th>6.5~7.0</th>
<th>7.0~8.0</th>
<th>8.0~8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>≤0.1</td>
<td>0.1~0.2</td>
<td>0.2~0.25</td>
<td></td>
</tr>
</tbody>
</table>

Figure 8 shows the microstructure of 7050-T7451 weld joint cross-section which is obtained under rotation speed of 700rpm, welding speed of 200 mm/min, tilt angle of 2.5° and welding force of 7.7 KN. The 7050-T7451 weld joint microstructure can be separated as four distinct zones, which are weld nugget zone (WNZ in A), thermo-mechanically affected zone (TMAZ in B), heat-affected zone (HAZ in C) and base metal zone (BM in D).

From macrostructures of figure 8, it can be seen that the weld joint is flawless under rotation speed of 700 rpm, welding speed of 200 mm/min, tilt angle of 2.5° and welding force of 7.7 KN,
which indicates that the set of parameters can ensure the quality of welding seam. Based on the microstructure of different areas, the grain structure of base metal presents lathy state with grain size longer than 100 um due to the rolling process. The weld nugget zone occurs dynamic recrystallization because the material in the middle of weld is stirred by tool and heated by frictional heating generated between tool and plate, which changes the microstructure of rolling to refinement equiaxed grains. In thermo-mechanically affected zone, material occurs plastic deformation and dynamic recrystallization. From microstructure of figure 8, it can be seen that the clear transitional zone appears between TMAZ and WNZ, while the transitional zone in AS is narrower than that of in RS, and the grain size in two sides of transitional zone is quite difference. The grain are elongated along boundaries around WNZ, which indicates the materials in this zone undergo major plastic deformation and heat cycle effect. In heat-affected zone, the structure has not significantly changed because of free-plastic deformation. However, the grain size becomes coarser than that of base metal and the microstructure and mechanical properties change a lot due to the heat cycle effect.

![Fig8 Microstructures of 7050-T7451 weld joint](image)

2 Experimental research on welding shrinkage mass

As the FSW floor component has high requirements on dimensional accuracy, while there will be welding shrinkage mass during the welding process, which will bring unpredictable impact on dimensional accuracy of the FSW floor component. So the research on welding shrinkage mass become very important, and also because the floor component has very complicated structure, the welding shrinkage mass research on prototype workpiece with the similar structure and large scale but not the test sample is needed.

Therefore, we designed the prototype workpiece with the similar structure and large scale as the floor structure, and on which we carried out the welding shrinkage mass research.
2.1 Experimental material and method

The parts (as shown in figure 10) of prototype workpiece are made from 7050-T7451 heavy-section extrusion (as shown in figure 9) by numerical control machining. The parts have complicated structure with many open slots and studs, and the thinnest and thickest wall thickness are 2mm and 7.5mm respectively, most of the structure thickness are between 3 to 5mm. The parts are 5.4m in length, 200 to 500mm in width. The prototype workpiece is made up of four parts by FSW, with the width of 1700mm after welding.

The measurement of prototype workpiece welding shrinkage mass is by measuring the related width dimensions t1 and t2 of the two parts before welding and \((t1+t2)\) 'after welding, and then the welding shrinkage mass will be calculated by \(\Delta t = (t1+t2) - (t1+t2)\).

2.2 Experimental results and analysis

Figure 11 shows the variation tendency of the prototype workpiece welding shrinkage mass along the welding direction and the average welding shrinkage mass value of different welding seam. The figure illustrate that the variation tendency of welding shrinkage mass along the welding direction is relatively small at the beginning stage of welding, while gradually increase to stable stage, with some data diverging. The welding shrinkage mass of welding seam 56z mostly vary from 0.3mm to 0.4mm, with the average welding shrinkage mass value of 0.33mm, the welding shrinkage mass of welding seam 67z mostly vary from 0.15mm to 0.25mm, with the average welding shrinkage mass value of 0.16mm, the welding shrinkage mass of welding seam 45z mostly vary from 0.1mm to 0.3mm, with the average welding shrinkage mass value of 0.18mm.

In general, the welding shrinkage mass of the prototype workpiece is within the range of 0.16~0.33mm.
The figure shows that some data diverge, the main reasons are:

1) Measurement errors. Because calculating the welding shrinkage mass need to measure many data, and the data diverging is mostly relate with the accumulation of measurement errors.

2) Complicated part structure. Complicated part structure results in complicated radiating conditions, in another word, there are many factors that can affect the
radiating, which result in data diverging.

3) Assembly condition of parts. Clamp force is hard to quantify, which result in the different force in different area, and then result in the different fit-up gap in different area, finally result in data diverging of welding shrinkage mass.

The welding shrinkage mass variation tendency of increasing from the very beginning to a stable stage then increasing slightly at the end is mainly related to the distribution tendency of welding temperature field along the welding direction. During the FSW process, the variation tendency of welding temperature field is “warming up-stabilizing-warming up”, which is because at the beginning of the welding process, the temperature increases to welding temperature from room temperature. During this stage, the frictional heat is absorbed by base metal and clamp, which result in relatively low temperature at the beginning, so the welding shrinkage mass is relatively small at the beginning. During the stabilizing stage of welding, the base metal has been heated completely, and the heat inputs are very stable, the heat outputs are by the way of thermal conductivity between base and backing plate, and clamp, which are also very stable. So during the stabilizing stage of welding, the welding temperature is relatively stable, and also the welding shrinkage mass is relatively stable. Before the end of the welding, because the tool is gradually moving to the end of the base metal, the radiating area between base metal, backing plate and clamp is decreasing, which result in the decreasing of heat outputs. And because the heat inputs are stable, while the heat outputs are decreasing, so the accumulation of the heat leads to the increase of the temperature at the end. That’s why the welding shrinkage mass increase slightly at the end of the welding seam.

3 Clamp design for floor structure welding

The distinct characteristics of the large floor structure are jumbo size of 19m in length and 1.5m in width, and complicated thin-wall structure, with many open slots and studs, and its wall thickness are between 2 to 4mm. The floor structure above determine that the welding reachability are not good. Therefore, in order to realize FSW of floor structure and ensure the welding quality, adopting the conventional design scheme is difficult to meet the requirements of welding process, so a set of specialized clamp for floor structure welding needs to be designed.

As for the FSW clamp design, there are three elements which are necessary:

1) rigid backing plate of back side of welding zone;
2) effective pressing on part surface adjacent to welding zone;
3) Effective pressing on two side faces adjacent to welding zone.

3.1 Rigid backing plate of back side and effective pressing device design

Considering that the parts of the floor are made from heavy-section plate by numerical control machining, the internal stress of the material will result in stress deformation after numerical control machining, the vacuum adsorbing backing plate (as shown in figure 13) is designed to ensure that binding face gap between back side of the part and backing plate meet the requirements of welding process. The ring groove of vacuum adsorbing backing plate was machined, which was sealed by sealing ring. And the vacuum adsorbing backing plates are connected with vacuum system, which can provide continuous adsorbing force, to adsorb the part of floor on the vacuum adsorbing backing plates. The experiments indicate that when the degree of vacuum reach 0.6bar, the binding face gap between back side of the part and backing plate is less than 0.1mm, which meets the requirements of welding process. At the same time, the vacuum system can provide 720N adsorbing force per meter on vacuum adsorbing backing plates, and the rest pressing force required by welding process is provided by air clamper (as shown in figure 14).
3.2 Effective pressing device on two side faces design

Because the parts of floor are thin wall structure with many open slots, and the space to carry out pressing are narrow. And also because the rigidity of floor parts are insufficient, the pressing force on two side faces are difficult to deliver.

![Pressing device on two side faces](image1)

Figure 15 Pressing device on two side faces

In the design process, we choose air-powered device to provide pressing force on two side faces. The lengthwise space of the parts are made full use of to lay the air-powered pressing device (as shown in figure 15) evenly. By the way of installing wedge block at the front-end of the air cylinder, the pushing force of air cylinder along the length direction is transformed into the pressing force on two side faces which is vertical to the welding direction.

In general, all the elements of clamp required by floor structure FSW are ready, which can meet the requirements of welding process.

4 Automatic control on long welding seam of floor structure

![Moving gantry FSW machine](image2)

Figure 16 Moving gantry FSW machine

The major difficulty of FSW complicated 19m long floor structure is how to
ensure the quality stability and uniformity of the whole welding seam. Automatic control is no doubt the best choice, because automatic control can avoid the uncontrollable factor brought about by manual control to reduce the probability of making mistake, so that the quality stability and uniformity of the welding seam can be ensured with maximum limit.

The welding equipment applied in the welding process of 19m floor structure is moving gantry FSW machine (as shown in figure 16), which has X direction maximum stroke of 28m, and can fulfill aluminum welding within 10mm thickness. The moving gantry FSW machine integrate force control technology and welding laser tracking technology (as shown in figure 17), during which measurement accuracy of the welding laser tracking is no less than 0.05mm. Force control technology can slightly and rapidly adjust the force value as the change of the welding thickness to adapt the change without affecting the weld joint quality stability and uniformity and its performance. Welding laser tracking technology can ensure that the moving trace of the tool is on the same track with the weld center line, even if the weld center line deviate the track slightly, the system can react rapidly to adjust the moving trace of the tool back to the right track. Using the welding laser tracking technology can reduce the workload of manual centering, and also reduce the probability of making mistake, which can ensure the welding quality with maximum limit.

5 Conclusion

1) By force control experimental research, the welding processing parameters are determined. With the welding speed of rotation 700rpm, welding speed 200mm/min, gradient of slope 2.5°, welding force 7.7KN, the 7050-T7451 FSW joint tensile strength exceed 90% that of base metal, and also obtain flawless weld joint, which meet the design requirements.
2) By welding shrinkage mass experimental research, the large FSW floor structure welding shrinkage mass, which is within 0.16mm to 0.33mm, was obtained. And also, the welding shrinkage mass variation tendency, which is increasing from the very beginning to a stable stage then increasing slightly at the end, was obtained.

3) Three clamp design elements required by large floor structure FSW process are met by adopting vacuum adsorbing backing plates as the rigid backing plate, by adopting vacuum adsorbing backing plates and air clamper as pressing force on surface, by adopting air-powered pressing device which transform the pushing force of air cylinder along the length direction into the pressing force on two side faces as the side faces pressing force.

4) In the welding process of 19m FSW floor structure, the force control technology and welding laser tracking technology are adopted to ensure the quality stability and uniformity of the whole welding seam.