Optimum Processing and Tool Controls for Three-Dimensional Friction Stir Welding

Hironori Takahara1,*1, Masato Tsujikawa1, Sung-Wook Chung2,*2, Yuzo Okawa3, Sachio Oki4 and Kenji Higashi1

1Department of Materials Science, Graduate School of Engineering, Osaka Prefecture University, Sakai 599-8531, Japan
2Division of Technology Licensing Organization Osaka Prefecture, 540-0029, Japan
3Technical Research Institute of Osaka Prefecture, Izumi 594-1157, Japan
4Department of Mechanical Engineering, School of Science and Engineering, Kinki University, Higashiosaka 577-8502, Japan

The influence of three-dimensional friction stir welding tool-control on joints' mechanical properties was investigated. Although FSW is widely applied to linear joints, it is impossible for five-axes FSW machines to maintain all FSW parameters in optimum conditions during three-dimensional (3D) welding. Such 3D FSW joints should be produced according to an order of priority for FSW parameters. Butt joints with rectangular change in the welding direction on a curved plane (curved L butt joints) were welded using different three tool-control methods, which change various welding parameters. Results show that the A and C axes shortcut method is effective for 3D welding.

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1. Introduction

Friction stir welding (FSW) is a new joining process for solid-state welding that uses frictional heat generated between a rotational tool and the material.1–3) If FSW were to become capable of producing three-dimensional (3D) joints, it would be increasingly applicable in many industries.4–8) However, it is difficult to maintain all welding parameters in appropriate permissible ranges because of the method’s limited degrees of freedom for tool control.9–13) Furthermore, it is also difficult for 3D welding to maintain the steady state of welding conditions as linear welding. Especially, in the area processed with rapid or discontinuous changes of welding parameters, which are unavoidable in 3D welding.

The welding parameters should be selected with priority because some parameters more strongly influence joint properties than others. The effects of non-selected parameters on the tensile properties were clarified by the selection of the parameter with priority. These results suggest guidelines for high-quality joints from 3D welding.

2. Experimental Procedure

2.1 FSW machine and welding condition

The machine used in this experiments has five degrees of freedom (DOF), an X–Y–Z driving axes, and an A and C rotational axes, as shown in Fig. 1. The welding material was a 5083-O aluminum alloy plate of 3 mm thickness. The tool used was made of JIS SKD61 tool steel. It has a 12-mm-diameter shoulder, 4 mm diameter, with a 2.85 mm length probe. The tool rotational speed is 800 rpm, the tool travel speed is from 100 to 200 mm/min, and the tool rotational direction is clockwise as viewed from above. It has been clarified that good joints can be produced in this welding condition.14,15)

2.2 3D FSW butt joints (curved L joints)

The material was bent to a curved shape with a radius of curvature of 150 mm; subsequently, material was cut to rectangular shapes in two pieces as shown in Fig. 2. These joints with rectangular change in the welding direction on a curved plate (curved L butt joints) were welded using different three different tool-control methods, as following;

(1) Tool inclination angle maintaining method (Welding speed altered): The inclination tool angles kept in 3 deg follow a curved plane through the welding. Figure 3 shows that it requires a rapid or discontinuous A and C axes change at the corner point to maintain the tool posture throughout the welding. Because it takes time to reset the tool posture for new welding direction, the welding speed is down to none during the posture reset.

(2) Welding speed-maintaining method (Zero inclination angle): The welding proceeds with zero tool...
inclination angles. Rapid or discontinuous tool head swinging is not necessary. The A and C axes profiles are also shown in Fig. 3. Incidentally, it has been clarified that the zero tool inclination angle method is an effective process in the plate plane, i.e. linear welding or two-dimensional (2D) welding.12,13)

(3) A and C axes shortcut method (Tool posture altered): The method avoids rapid or discontinuous A and C axes changes. Figure 3 also shows the change in angles of A and C axes during the A and C axes shortcut method used in this experiment. This method produces deviations of tool posture from appropriate conditions. Figure 4(a) shows the deviation from proper zero angle in pitching or rolling angle of the tool. But the deviation was set to within the limits of the permitted range shown in Table 1 to control the amount of A and C shortcut, as shown in Fig. 4(b).

Tensile specimens were cut from the curved L joints as shown in Fig. 2.

3. Results and Discussion

The joints produced by each tool-control method are shown in Fig. 5. The joints produced by the tool inclination angle maintaining method had a crack at the corner point, as shown in Fig. 5(b). The joints produced by the welding speed maintaining method had a continuous groove at the weld bead, as shown in Fig. 5(c). The joints by the A and C axes shortcut method had no surface defects, Fig. 5(d).

Cross section views of the joints are shown in Fig. 6. The linear welding specimen is shown in Fig. 6(a) as a reference. The advancing side is the left side of the picture. The specimen of the tool inclination angle maintaining method has no defects, and the hardness profile is as good as that of the linear welding specimen, Fig. 6(b). A groove was observed in the specimen of the welding speed maintaining method, Fig. 6(c). Such grooves are caused by insufficient frictional heat input.16) The stir zone grain size are 2.8 μm, 7.0 μm, 5.2 μm and 6.0 μm for the welding speed maintaining method, linear welding, the tool inclination angle maintaining method and the A and C axes short cut method, respectively. Figure 6(c) shows the highest stir zone hardness. These results confirm the low processing temperature due to insufficient tool pressure.

The cross sections of the corner points are depicted in Figs. 6(d), 6(f). The specimens produced by the tool inclination angle maintaining method and the A and C axes
shortcut method show no defects and a hardness profile that is as good as that of linear welding specimens. In contrast, the specimens of welding-speed maintaining method have defects. Observations of the cross section of the specimens indicate that the 3D FSW requires tool inclination angles.

The results of tensile test are shown in Fig. 7 as the average of three specimens. The mechanical properties of the joints made by the A and C axes shortcut method are as good as those from linear welding. The joints ruptured at the base metal. The joints produced by the tool inclination angle maintaining method and the welding speed maintaining method showed lower tensile strength than that of the linear joint. These joints ruptured at the stir zone along the defects.

Previous reports\textsuperscript{13)\textsuperscript{14}} shows the allowance range of tool inclination angles, as shown in Table 1. The good welded joints can be made with tool inclination angles between 0 and 3 deg. Tensile strength decreased rapidly if the tool inclination angles step into the minus range.\textsuperscript{13)\textsuperscript{14}} It is thought that the sufficient pressure from tool cannot be loaded in the minus range of the tool inclination angle.

The work shape is a curved plane in 3D welding. For that reason, the relationship between the work and tool front produces the same conditions as when tool inclination angles are in the minus range in plane plate welding. Figure 8 shows that the tool inclination angle is $-2^\circ$, as calculated for the work with the radius of curvature of 150 mm and tool shoulder diameter of 12 mm. The value, $-2^\circ$, is out of the allowance range. Zero inclination angle welding is effective for 2D welding,\textsuperscript{13,14)\textsuperscript{14}} but results showed that the proper tool inclination angle is necessary in 3D welding.

Welding speed is an important parameter for FSW. The welding speed stalled at the corner point in the tool inclination angle maintaining method because welding cannot resume until the tool posture is reset to a proper value. This stall of welding speed produces defects and deteriorates the joint’s mechanical properties. Although the joints produced by the A and C axes shortcut method were welded with unstable welding speed, the relative speed of the tool against the work-piece did not down to zero. Consequently, the joint properties are good. It is important to maintain the welding speed in proper range.

4. Conclusion

Good joints can be produced by the A and C axes shortcut method. Results of this experiment clarify that the 3D welding requires the proper tool inclination angles corre-
sponding to the plate curvature. Joints strength can be as good as those produced by linear welding by optimizing
the tool-control method in unstable areas.

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