Suppression of root flaw in friction stir welded 6061-T6 aluminum alloy using double spiral tool *

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Friction Stir Welding (FSW) has been attracting attention for its usefulness such as relatively easy joining compared to conventional arc welding, and its application to industries is being expanded, for example thick aluminum plates for infrastructures. FSW is known to yield defects called root flaws depending on welding conditions. In order to suppress the defects, it is necessary to optimally control the plastic flow and to stir the materials to be welded cooperatively. The present study tried to make a sound joint of 6061-T6 aluminum alloy sheets with 3 mm in thickness using a newly designed tool called “Double Spiral Tool” which can increase the volume of the stir zone around the tool. Two types of tools were used: a normal type with M4 to M3 screws (called single spiral tool) and a “double spiral” type with the same pitch and twice amount of lead length. The welding tests revealed that the root flaw was completely disappeared with the double spiral tool under the welding condition of 900rpm-50mm/min, while it still remained in the joint produced by the single spiral tool. Thus, the present study successfully proved that the double spiral tool is effective to suppress the root flaw in FSW joints of 6061 aluminum alloy.

Key Words: aluminum alloy, Friction Stir Welding (FSW), double-spiral tool, root flaw, 6061-T6 aluminum alloy, tool shape

1. Introduction

Aluminum alloys have been contributing to many industries such as energy conscious engineering such as vehicles, and also infrastructures to meet the demand of long lifecycle cost because of their high specific strength together with high formability.

Joining is also a key to the aluminum engineering, and especially friction stir welding (FSW) is the most promising one. FSW is a welding method developed at The Welding Institute (TWI) in 1991, and is a kind of welding method using the frictional heat generated between the welding tool and the workpiece, where the process temperature is mostly below the liquidus (1). Dependability of FSW joints free of defects is strictly relevant to the plastic flow around the rotating FSW tool. The flow behavior is functions of friction between the tool and the materials, process temperature, and the properties of base materials such as flow stress, strain rate at elevated temperature.

Since the plastic flow depends on the shape of the welding tool a great deal of research has focused on the dimensions of tool shapes such as probe and shoulder (3)-(4) as well as the joining conditions (5)-(22). Most commonly used tools for FSW are composed of threaded probe that is designed to promote effectively a helical vertical rotational flow along the axis of probe, so as the mass transport near the tool as the tool rotates.

The larger the effective transport volume per rotation, the wider the range of plastic flow i.e., the stirring effects is expected. Therefore, defects formed near the bottom surface of the joint, such as the root flaw in butt joints, is expected to be suppressed more effectively by enhancing the volume of material being transported around the welding tool. This contributes to produce sound joints even for thicker aluminum materials to be utilized for infrastructures such as bridges. In other words, the design of a tool shape that has the function of effectively increasing the amount of plastic flow or the plastic flow range is indispensable for improving the reliability of FSW joints.

Based on this, the present work designed and manufactured a double-thread screw (called a double spiral tool) to evaluate the enhancement of plastic flow to suppress the root flaw.

2. Experimental procedure

2.1 Tool design

Two types of FSW tools made of SKD61 steel with left screwed probe but different dimensions of thread, as schematically illustrated in Fig. 1, were adopted for the welding tests. The pitch is the distance between two adjacent threads, and the lead means the distance of screw advance per rotation. The symbols of (1) and (2) in Fig. 1 shows threads: Fig. 1 (a) is a normal type screw with a one thread of (1), and Fig. 1 (b) is a double-thread screw with two threads of (1) and (2). The common dimensions for these tools are shoulder diameter and the probe length which are 12 mm, and 2.5 mm, respectively. Also, the probe has a truncated cone shape.
from 4 mm at the bottom to 3 mm at the top.

Figure 1(a) is a conventional type with a single spiral thread of which has the same amount of both pitch and lead. Figure 1(b) is a newly designed tool called “double spiral tool” where the value of lead is twice as large as that of the pitch\(^5\). Thus, the double spiral tool is theoretically expected to perform double amount of mass transportation to promote wider range of stirring region to eliminate defects such as root flaw during FSW.

2.2 Materials

A6061-T6 aluminum alloy with a dimension of 3 mm of thickness, 80 mm of width, and 225 mm of length was used for the present welding tests. The chemical composition is shown in Table 1.

2.3 FSW tests

A two-dimensional friction stir welding machine (Hitachi, 2D-FSW) was used for the present FSW tests. The welding tests were performed with three tool rotation speeds such as 600, 900 and 1200 rpm, and three welding speeds such as 50, 150 and 250 mm/min. for each rotation speed. The welding length, tool advance angle, and tool plunge depth, and dwell time are 150 mm, 3 degrees, 0.2 mm, and 3 s, respectively.

2.4 Evaluation of joint microstructure

Cross-sectional macrostructures, mainly focused on the size of stirred zone and the length of root flaw, were observed with an optical microscope (Olympus, BHM-51M) for the each joint produced under several welding conditions. Specimens for the observation were cut from the joints, followed by a series of mechanical polishing, mechano-chemical polishing, and chemical etching with 10% sodium hydroxide solution for 210 s.

3. Results

Figure 2 shows a comparison of macroscopic views on the cross-sections of the joints produced under the welding condition of 600 rpm-50 mm/min. (a) and (b) are for the cases of single and double spiral tools, respectively. The widths of stirred zone (SZ) at the middle-thickness position for single and double spirals are 8.7 mm and 9.3 mm, respectively. Thus, the double spiral tool enhanced the stirring action as expected.

Figure 3 shows enlarged views of the region near the bottom of the test piece (600 rpm-50 mm/min).
spiral case was 650 µm, whilst the double spiral tool reduced the length down to 260 µm, that was 60% less than the single spiral case.

The double spiral tool has a potential to enhance the stirring action and hence the defect formation could be effectively suppressed when the rotation speed raised where plastic flow is much more activated, which will be proved in the following figures.

Figure 4 shows a comparison of macroscopic views on the cross-sections of the joints produced under the welding condition of 900 rpm-50 mm/min. (a) and (b) are for the cases of single and double spiral tools, respectively. No clear defects such as cavities nor large cracks are observed for both joints. The widths of stirred zone (SZ) at the middle-thickness position for single and double spirals are 7.8 mm and 8.0 mm, respectively. Thus, the double spiral tool enhanced the stirring action as expected.

Figure 5 shows enlarged views of the region near the bottom of the plates as shown in Fig. 4. Root flaws of 250 µm was also observed in the joint by the single spiral tool, while the double spiral tool yielded no defect in this region. Thus, the double spiral tool perfectly suppressed the defect formation under this welding condition.

4. Discussion

The present experimental results as shown from Fig. 2 through 5 clearly indicate that the suppressing effect of defect formation by the double spiral tool was confirmed. As mentioned above, the enhancement of mass transportation by the double spiral shaped probe is a key to understand the mechanism of defect suppression at the bottom region of the joint. The double amount of mass transportation increases the volume of SZ as well as its radius. As explained in Fig. 3, the width of SZ increased by 6.9% in the case of 600 rpm, which is not sufficient to eliminate the root flaw.

This can be considered from two viewpoints such as 1) temperature, and 2) plastic flow along the probe and under the shoulder. Since FSW is fundamentally a sort of high temperature deformation, the temperature distribution around the tool is an important factor affecting the flow behavior. The flow stress of metals normally decreases as the deformation temperature raises, so higher rotation speed, which promotes larger amount of frictional heat, is effective to enhance the amount of mass flow. The distribution of temperature around the tool is another factor affecting the growth behavior of SZ. The growing SZ is pushing aside the neighboring region where the temperature is relatively lower, i.e., the flow stress is higher. So, the balance of the forces by the growing SZ and the reaction force by the neighboring region makes the stable size of SZ. Therefore the higher rotation speed is important to eliminate the root flaw because of the higher temperature and also wider temperature distribution to increase the amount of softened volume around the tool.

A discharged mass from the stirring area around the tool, which is called burr, is also relevant to the tool dimension as well as the welding conditions. The double spiral tool tended to yield larger amount of burr than the single spiral one. Thus, the burring action reduces the efficiency of defect elimination because of reduced mass that should have filled the flaw. Consequently, the role of shoulder is necessary to be optimized properly to prevent the burr
for the sake of increasing the amount of mass that effectively eliminates the flaw formation.

The idea of double spiral tool that has a function to increase the amount of mass transfer is effective and useful to produce sound FSW joints by suppressing the root flaw. The double spiral tool is also expected to produce sound joints for thicker plates that are used in infrastructures, and also to increase dependability for the FSW process even for the workpieces with fluctuating thickness. Thus, the application of double spiral tool would become wider in future.

5. Conclusion

The present study performed FSW tests on 6061-T6 aluminum alloy plates with two types of welding tools such as single and double spiral tools to verify that the double spiral tool can effectively suppress the formation of root flaw in the FSW joints. The following results were obtained.

1) The double spiral tool reduced the length of root flaw by 60% of that of the single spiral tool under the condition of 600 rpm-50 mm/min.
2) The root flaw was completely disappeared with the double spiral tool under the welding condition of 900 rpm-50 mm/min, while it still remained in the joint produced by the single spiral tool.

These results clearly lead us to the conclusion that the double spiral tool is effective to suppress the root flaw in FSW joints of 6061 aluminum alloy.

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