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Three defect types in friction stir welding of aluminum die casting alloy

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Abstract

For different tool plunge downforces, the optimum FSW conditions of aluminum die casting alloy were examined. The higher the tool plunge downforce is, the wider the range of the optimum FSW conditions is. The following three different types of defects are formed, depending on the FSW conditions. (1) A large mass of flash due to the excess heat input; (2) cavity or groove-like defects caused by insufficient heat input; and (3) cavity caused by the abnormal stirring. As for the abnormal stirring, it is clearly seen that the shape of the top part on the advancing side in the stir zone is completely different. For this type of defect, the effect of the tool plunge downforce is small, though the size of the defect due to insufficient heat input significantly decreases with the increasing downforce.

Keywords: FSW; Aluminum die casting alloy; Tool plunge downforce; Optimum; Joint; Defect

1. Introduction

Conventional fusion welding of aluminum die casting alloys is generally difficult due to the formation of blowholes by entrapped H_2 gas and the fragile intermetallic compounds in the weld metal. Accordingly, a new welding method is required to solve these problems. In recent years, friction stir welding (FSW) was developed as a solid state joining process in 1991 at TWI [1]. This process is effective for the welding of various aluminum alloys. However, only a limited number of studies have been carried out on die casting and cast aluminum alloys [2–6].

FSW enables materials to be joined below their melting point T_M and the cast structure to be modified because of grain refinement, the fine dispersion of intermetallic compounds, no formation of blowholes with removing cast defects and the dendritic structure of the base metal. Also, dissimilar joining with wrought alloys can be performed by FSW [2,7,8].

As already described, the application of FSW to aluminum die casting alloys has a significant practical concern from the view point of industrial use. Accordingly, the determination of the optimum FSW conditions is very important. The optimum FSW conditions have been discussed for several aluminum alloys [9–11], however the mechanism of the joint defect formation during FSW has not been discussed in detail.

The aims of this study are to examine the weldability of ADC12 FSW joints obtained by the load control type of the FSW machine and to evaluate the effect of the welding parameters on the joint quality. Based on these results, the mechanisms of the joint defect formation during FSW are classified.

2. Experimental procedures

Four-millimetre thick ADC12 aluminum die casting alloy plates were used in this study. The gas content of the plate was about 2.6 ml/100 g Al. Table 1 shows the chemical compositions of the ADC12 base material. These plates are 300 mm long, 100 mm wide and 4 mm thick.

To evaluate the range of the optimum welding conditions for ADC12, stir-in-plate welding was performed using load control type FSW machine. The tool has a columnar shape with a screw probe. SKD61 was used as the tool material. The diameter of the shoulder was 15 mm. The diameter and the length of the probe were 5 and 3.9 mm, respectively. Mild steel was used for the backing plate. The tilt angle was 3°.

The tool plunge downforce was changed from 6.9 to 14.2 kN. The tool rotation speed in the clockwise direction and the welding speed were changed from 500 to 1500 rpm and from 250 to 1000 mm/min, respectively.

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Table 1
Chemical compositions of ADC12 base material

Alloy	Chemical compositions (mass%)
Cu	2.35
Si	11.82
Mg	0.17
Zn	0.56
Fe	0.81
Mn	0.18
Ni	0.04
Sn	0.02
Pb	0.06
Al	Balance

Visual and X-ray radiography inspections of the FSW joints were performed in order to reveal the weld defects on the surfaces and in the inner zones of the welded joint. Metallurgical inspection was performed on the cross-sections of the FSW joints. They were polished and etched with a 5% hydrofluoboric acid (HBF_4) water solution for the optical microscopic observations.

3. Results and discussion

3.1. Inspection of FSW joint

Fig. 1 shows the typical appearances of the joint surfaces, X-ray radiographies and macroscopic structures of the cross-sections of the FSW joints at the constant tool rotation speed of 1500 rpm.

For the tool plunge downforce of 6.9 kN at the welding speed of 250 mm/min, it is clearly seen that a sound joint was obtained. However, an inner defect, such as cavity, is observed inside the joint at a high speed of 500 mm/min. This defect cannot be seen on the surface, though it was revealed that a defect linearly exists along the joint line by X-ray radiography inspection. At the higher speed of 750 mm/min, a groove-like defect is formed in the joint surface.

3.2. Optimum FSW condition of ADC12

Fig. 2 shows the relationship between the welding parameters and the optimum FSW conditions for an aluminum die casting alloy of ADC12. For each given tool plunge downforce, sound joints are obtained at the appropriate tool rotation speeds and welding speeds. At the highest tool plunge downforce of 14.2 kN, the range of the optimum FSW conditions was wider than the others. The increase in the range of the optimum FSW conditions was small when the tool plunge downforce changed from 11.8 to 14.2 kN compared with that from 6.9 to 9.3 kN and from 9.3 to 11.8 kN. When the downforce increases, the range of the optimum FSW condition of ADC12 is mainly enlarged to a lower rotation speed and higher welding speed range. On the other hand, the boundary for the higher rotation speed and higher welding speed range is not significantly affected by the downforce.

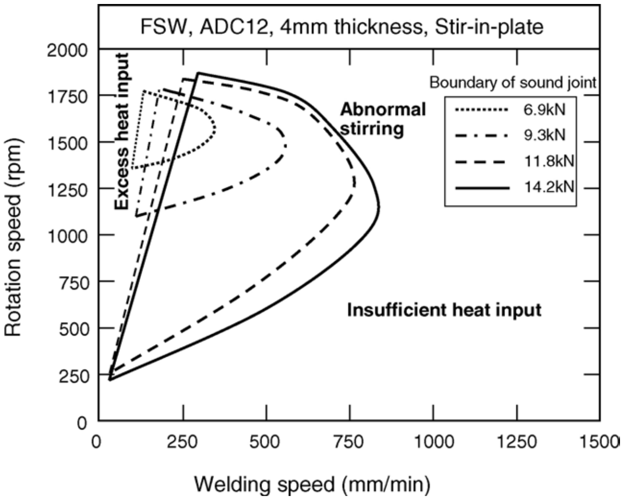

Fig. 2. Range of the optimum FSW conditions for each tool plunge downforce.

3.3. Types of defect formation

Defects are formed outside the optimum FSW conditions. However, the following three different types of defects are formed, depending on the FSW conditions.

(1) a large mass of flash due to the excess heat input;
(2) cavity or groove-like defect caused by an insufficient heat input;
(3) cavity produced by the abnormal stirring.

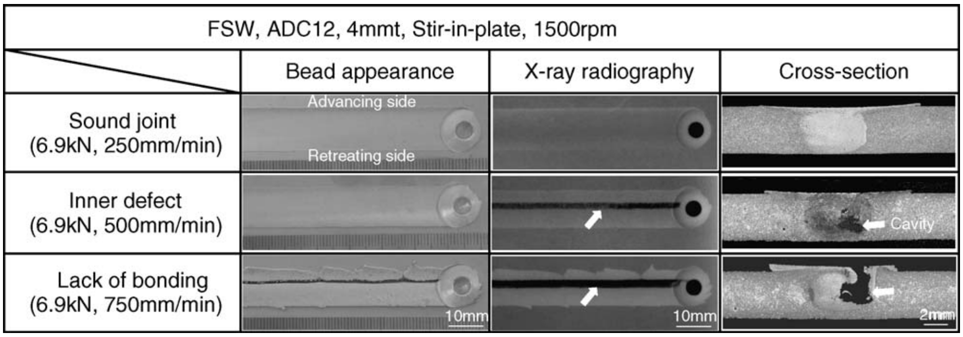

Fig. 1. Inspection of FSW joints by visual, X-ray radiography and cross-section.

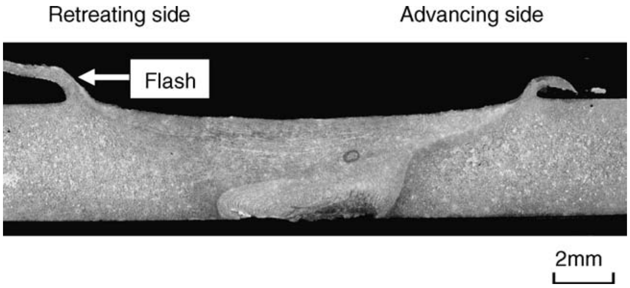

Fig. 3. A typical joint defect caused by excess heat input.

As for the excess heat input (1), the cross-section of a typical FSW joint is shown in Fig. 3 for the tool plunge downforce of 14.2 kN, the rotation speed of 1750 rpm and the welding speed of 250 mm/min. These types of defects are formed at a higher rotation speed and a lower welding speed, namely in the left-hand side outside the optimum FSW conditions in Fig. 2. The large mass of flash was ejected to the outside due to the softening of the metal by the excess heat input during the FSW. In this case, the tip of the tool probe sometimes touches the backing plate.

As for the insufficient heat input (2), defects are formed at the lower rotation speed and the higher welding speed, namely in the right-bottom side of the optimum FSW condition in Fig. 2. A cavity or groove-like defect was primarily caused by an insufficient heat input during the FSW. Although the defect formations due to the excess or insufficient heat input were reported in previous FSW studies [12], defect formation due to abnormal stirring has not yet been reported. Such details will be discussed in Section 3.5.

3.4. Defects due to excess and insufficient heat input

Frigaard et al. [13] suggested the following equation describing the heat input during the FSW:

$$q = \frac{4}{3}\pi^2 \mu PNR^3 \tag{1}$$

where q is the heat input, μ is the friction coefficient, P is the pressure, N is the rotation speed and R is the radius of the shoulder. From Eq. (1), if the heat input per unit length, Q, is considered for the moving welding, Eq. (2) is obtained.

$$Q = \frac{\alpha q}{V} = \frac{4}{3}\pi^2 \frac{\alpha \mu PNR^3}{V} \tag{2}$$

where α is the heat input efficiency and V is the welding speed. When α, μ and R are assumed to be constant, Eq. (3) is derived from Eq. (2).

$$Q \propto \frac{PN}{V} = Pa \propto Fa \tag{3}$$

where a is the slope of the welding speed versus the rotation speed and F is the tool plunge downforce. Table 2 shows the minimally required heat input, which is calculated using Eq. (3), for each tool plunge downforce. In this case, the slope was obtained by the tangent line with the bottom side of the boundary line under the optimum FSW conditions for each tool plunge downforce. From this result, as the tool plunge downforce decreases, the calculated minimum heat input increases. In particular, the value significantly increases for downforces lower than 11.8 kN.

Table 2
Calculation of the minimally required heat input for each tool plunge downforce

Downforce, F (kN)	Slope, a (mm^{-1})	Fa (kN mm^{-1})
6.9	2.55	17.6
9.3	1.45	13.5
11.8	0.86	10.2
14.2	0.64	9.1

Fig. 4 shows the cross-section and the end part of the FSW joints at the tool rotation speed of 1500 rpm, and welding speed of 250 mm/min for each tool plunge downforce. In the macroscopic structure, the top surface contact with the tool shoulder was observed as a concave part, and the stir zone was seen in the center of the joint. The contact area width of the tool shoulder becomes larger with the increasing tool plunge downforce. In the end part, the shoulder was not in complete contact with the workpiece at the lower tool plunge downforces of 6.9 and 9.3 kN because the tilt angle was 3°. The tool shoulder made completely contact with the workpiece when the tool plunge downforce is 11.8 kN or larger.

3.5. Defect due to abnormal stirring

As for the abnormal stirring (3), defects are formed at higher rotation speeds and higher welding speeds, namely in the right-upper side of the optimum FSW conditions, as shown in Fig. 2. It is considered that the abnormal stirring is caused due to the different temperatures between the upper part near the surface and the lower part. Fig. 5 shows the change in the cross-sections with the changing the rotation speed for each tool plunge downforce. From this result, it is found that the shape of the defects is similar for both types. As a result, the third type of defect has never been mentioned before. However, there are clearly some different points between the insufficient heat input and abnormal stirring cases as follows:

(1) shape of the stir zone on the cross-section;
(2) dependence of the tool plunge downforce on the defect size.

The shape of the stir zone for an insufficient heat input has almost the same shape as that of a sound joint. However, in the case of the abnormal stirring, it is clearly seen that the shape of the top part on the advancing side in the stir zone is completely different. This different shape indicates that the flow of the material is discontinuous. The defect size under the insufficient heat input conditions was significantly decreased with the increasing tool plunge downforce. It is thought that the defect can be pressed by a larger downforce. As for the abnormal stirring, on the other hand, the effect of the tool plunge downforce was small, though the defect size gradually becomes smaller with the increasing downforce.

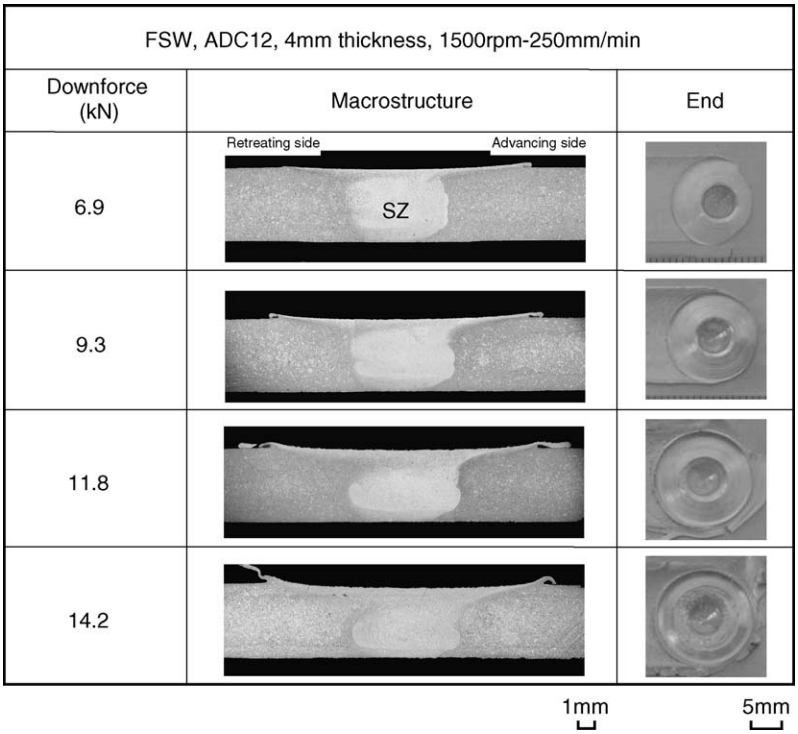

Fig. 4. Effect of tool plunge downforce on the joint formation.

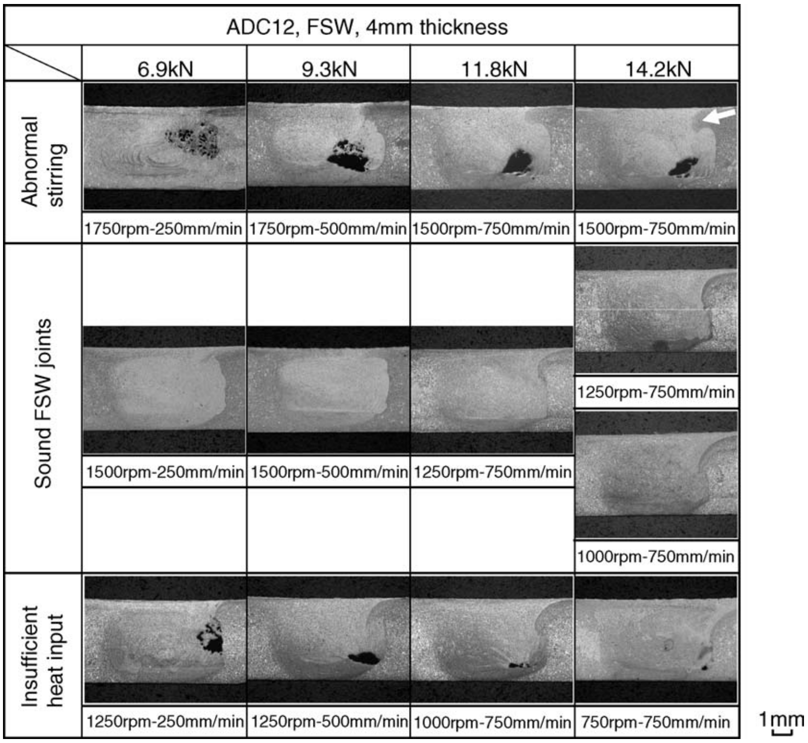

Fig. 5. Difference in cross-section between the insufficient heat input and the abnormal stirring conditions.

4. Conclusions

For each given tool plunge downforce, sound joints are obtained at appropriate tool rotation speeds and welding speeds. At the highest tool plunge downforce of 14.2 kN, the range of the optimum FSW conditions was wider than the others.

Three different types of defects are formed, depending on the FSW conditions. (1) A large mass of flash due to the excess heat input; (2) cavity or groove-like defects caused by insufficient heat input; and (3) cavity caused by the abnormal stirring.

As for the abnormal stirring, it is clearly seen that the shape of the top part on the advancing side in the stir zone is completely different. For this type of defect, the effect of the tool plunge downforce is small, though the defect size gradually decreases with the increasing downforce.

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