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Short Communication

Effect of weld curvature radius and tool rotation direction on joint microstructure in friction stir welding casting alloys

Wenya Li [a,*], Qian Yang [b], Zhihan Zhang [a], Dalu Gao [a]

[a] State Key Laboratory of Solidification Processing, Shaanxi Key Laboratory of Friction Welding Technologies, Northwestern Polytechnical University, Xi'an 710072, Shaanxi, PR China
[b] School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China

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ABSTRACT

Curved welds were designed and the effects of the weld curvature radius and tool rotation direction on the microstructure of friction stir welded cast aluminum alloy joints were investigated. Results show that both the weld curvature radius and tool rotation direction have a significant influence on the microstructure of the curved joints during FSW. With decreasing weld curvature radius, the size of the tunnel defect is reduces and the proportion of fine Si particles in the stir zone increases. Si particles are finer and denser in the retreating side (RS) than that in the advancing side (AS) when both the welding direction and tool rotation direction are anticlockwise. However, when the welding direction is anticlockwise while the tool rotates clockwise, the proportions of fine Si particles decrease compared to the former situation. Furthermore, the tunnel defect is more likely to be present in the AS in the former situation.

1. Introduction

Cast aluminum alloys present a good combination of cost, strength and corrosion resistance while they can be formed easily using die casting due to their excellent fluidity [1]. Hence, cast aluminum alloys have been widely applied in automobile applications replacing steel for weight saving. It is therefore necessary to weld aluminum castings to themselves or to wrought alloys for various applications. However, numerous efforts to weld these alloys by conventional fusion welding have shown that fusion welding is not suitable because the quality of the welded joint is lower due to the development of pores, hot cracking and distortion defects in the joint.

Friction stir welding (FSW) is an innovative solid state welding process which can join light metallic structures using aluminum and magnesium alloys, which are widely applied in the aerospace, automobile and shipbuilding industries [2,3]. FSW creates a joint without bulk melting and thus with no defects as the porosity and hot cracking. As a consequence of this, welds made with FSW are shown to have much improved mechanical properties compared to fusion welds [4–6]. A number of interesting papers have been presented in literature on FSW of aluminum alloys [7–12]. Mofid et al. [7] concluded that submerged FSW created fine grained welds and alleviated formation of intermetallic phases. Liu et al. [12] found that underwater FSW improved the strength of normal FSW joints. Sarkari et al. [13] revealed that after FSW specimens strained by constrained groove pressing, grain growth with the corresponding hardness reduction was observed at the stir zone. Hu et al. [14] investigated the tensile plastic deformation characteristics of friction stir welded 2024 aluminum alloy and found that the differences in regional strain of the joints resulted in a decrease of the overall mechanical properties. Magdy et al. [15] focused on the influence of multi-pass friction stir processing on the microstructure and mechanical properties of aluminum alloy 6082 and illustrated that the accumulated heat due to multiple passes resulted in an increase of the grain size, dissolution of precipitates and fragmentation of the second phase particles. On the other hand, increasing the welding speed did not affect the grain size, although it reduced the particle size and increased the particle area fraction. Jayaraman et al. [16] developed an empirical relationship to predict the tensile strength the friction stir welded cast aluminum alloy using RSM. Elangovan et al. [17] developed an empirical relationship to predict the tensile strength of the friction stir welded joints of AA2219 Al alloy by means of RSM. Lombord et al. [18] proposed a systematic approach to optimize FSW process parameters (tool rotational speed and feed rate) through consideration of frictional power input. Rajakumar et al. [19] proposed models using RSM to predict tensile strength of FSW joints of AA7075 Al alloy. Zhu et al. [20] developed relationships between micro-hardness and nano-hardness of dissimilar welding joints of newly developed rotor steels. However to date all reported studies have focused on straight welds, while FSW with a curved weld path have not been presented. In fact, in the aerospace and automotive industries the curved welds are one of the most common welds. It is expected that in the curved welds the effect of the curvature radius on the microstructure and mechanical properties of FSW joints may be of great importance, as the curvature radius will

* Corresponding author. Tel.: +86 29 88495226; fax: +86 29 88491426.
E-mail address: liwy@nwpu.edu.cn (W. Li).

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Table 1
Chemical composition of 3522 AlSi cast aluminum alloy [21].

Si	Cu	Mg	Zn	Fe	Mn	Ti	Al
12.0	0.05	0.005	0.1	1.0	0.001–0.4	0.15	bal.

result in a difference in welding speeds between the advancing side (AS) and the retreating side (RS). In the present research, the effects of tool rotation direction and curvature radius on the microstructure of curved weld were investigated.

2. Experimental procedures

Cast aluminum alloy plates of 3522 AlSi, 5 mm thick and 110 mm in length by 60 mm in width, were used in this study. The chemical composition of the base metal (BM) is shown in Table 1 [21]. The plates were butt-welded using a CNC milling machine (XKA5032, Nantong Machine CO., Ltd., China) using a welding and rotation speed of 150 mm/min and 1500 rpm respectively. The size of the H13 steel tool and the process parameters used in this study are shown in Tables 2 and 3 respectively. The welding direction used in this study is anticlockwise. The weld curvature radius of 9.8 mm and 30 mm were used to investigate the effect curvature radius has on the microstructure in the curved welds. Furthermore, in order to investigate the effect of tool rotation direction on the microstructure of the joint, the tool rotation direction was changed from clockwise to anticlockwise. After welding, the joints were cut perpendicular to the welding direction for metallographic analysis. The microstructure analysis of joints was performed with an optical microscope (OM) and a scanning electron microscope (SEM).

3. Results and discussion

3.1. Actual welding speed in the curved weld

In the curved weld, the curvature radii at AS and RS are different as shown in Fig. 1. When the tool rotates anticlockwise and the shoulder diameter is 8 mm, the actual curvature radii at AS and RS are "$R + 4$" and "$R - 4$", respectively. Therefore, assuming that the welding speed is V (mm/min), the actual welding speeds at AS (VAS) and RS (VRS) can be calculated with the following equations:

$$\mathrm{VAS} = \frac{V}{R}(R + 4) \tag{1}$$

$$\mathrm{VRS} = \frac{V}{R}(R - 4) \tag{2}$$

The VAS and VRS change with radius R at a welding speed of 150 mm/min is shown in Fig. 2. It can be seen that the smaller the weld curvature radius is, the greater is the effect it has on the actual welding speeds at AS and RS. Moreover, with increasing weld curvature radius the smaller is the speed difference.

According to Eqs. (1) and (2), the VAS and VRS were calculated in the present research as shown in Table 4. It can be seen clearly that when the weld curvature radius is 9.8 mm, the actual welding speeds at AS and RS are 211.14 mm/min and 88.74 mm/min, respectively. Due to this difference there may be differences in the microstructure at AS and RS in the FSW joints.

Table 2
Dimensions of the H13 steel tool.

Shoulder diameter (mm)	Probe diameter (mm)	Probe length (mm)
8.0	3.0	3.0

Table 3
Process parameters of FSW experiment.

No.	Rotation speed (rpm)	Welding speed (mm/min)	Tool rotation direction	Weld curvature radius (mm)
1#	1500	150	Anticlockwise	9.8
2#	1500	150	Anticlockwise	30
3#	1500	150	Clockwise	30

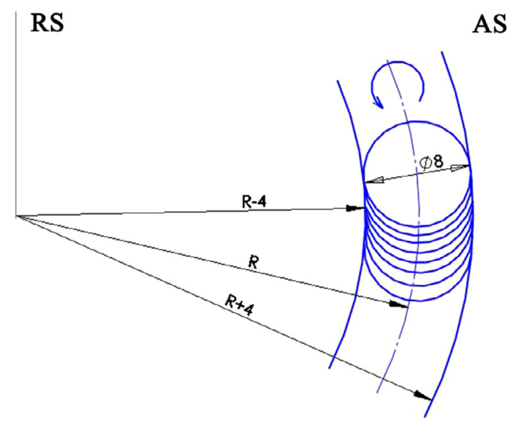

Fig. 1. Schematic of the curved weld (unit: mm).

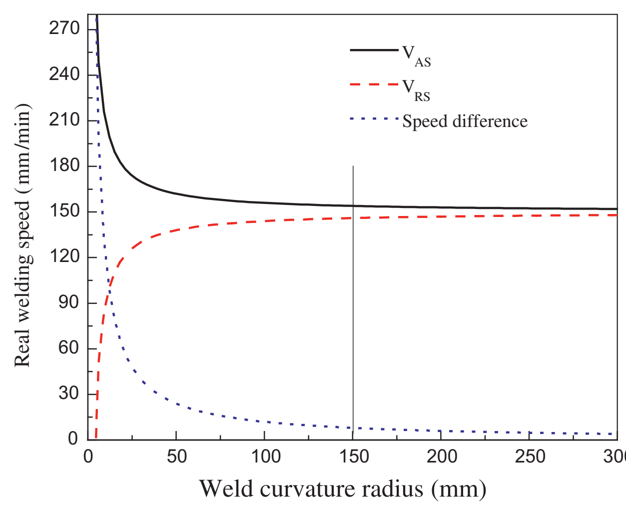

Fig. 2. Change of VAS and VRS with weld curvature radius.

Table 4
Real welding speeds at the AS and RS.

Curvature radius (mm)	V (mm/min)	VAS (mm/min)	VRS (mm/min)
9.8	150	211.14	88.74
30	150	170.00	130.00

3.2. Microstructure of joints

Fig. 3 shows the microstructure of BM. The BM has a dendritic microstructure with primary α-Al phase and eutectic phase. The needle-like eutectic phase is mainly distributed in the grain bound-