Influence of an electric field on the microstructures and properties of the friction-welded joint of LY12 alloy

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By means of microstructure observation, hardness test and torsion strength test, some characteristics of the friction welded joint undergoing an external electric field have been studied quantitatively. The recrystallization grain size in the weld metal zone (WMZ) decreases when the external electric field is applied. The equiaxed grains in the dynamic recrystallization zone (DRZ) increase and the equiaxed characteristic of recrystallization grains in the DRZ is enhanced. The microstructure of the welded joint along the axial direction becomes more homogeneous. When the same friction welding parameters are applied, the electric field causes an increase in the width of the DRZ. Moreover, the external electric field effect leads to the hardness of the welded joint increasing, and also homogenizes the hardness distribution along the radial and axial directions. In addition, the average torsion ductility of the weld metal increases in the case of applying the external electric field.

1. Introduction

Previous studies indicated that an external electric field has significant influence on superplastic deformation [1], heat treatment [2, 3], recrystallization [4] and phase transformation [5] of metallic materials. It is generally believed that the electric field or pulse electric current has influenced the behaviors of vacancies, dislocations and grain boundaries, which led to the microstructure rearrangement.

The effect of electric filed on the superplastic deformation behavior of 7475 aluminum alloy has been investigated by Cao *et al.* [1]. Their results showed that the superplastic flow stress and strain hardening were reduced and the strain rate sensitivity of the flow stress was increased by the external electric field. In addition, the electric field reduced the cavitations and grain growth, which occurred during the superplastic deformation. The mechanism related to the deformation involves the motion of lattice defects (vacancies or dislocations), which are known to be influenced by the electric field or current [1, 6]. In the view of this, it is anticipated that an external electric field may have some favorable effects on the deformation behaviors of the weld zone during the friction welding process, which could have practical importance as well as scientific interests.

However, it should be noticed that almost all the former research work was performed under single tensile test or single compression test conditions, which are different from the real deformation conditions during the friction welding process. The purpose of this work is to study the dynamic recrystallization of the weld zone during the friction welding process of duralumin LY12 in the presence of an electric field. We expect to reveal the effects of the electric field on the microstructure, especially on the grain size and the width of the recrystallization zone (including the DRZ and the WMZ) of the welded joints. The electric field effect on the hardness distribution and some mechanical properties of duralumin LY12 will also be discussed.

2. Experimental procedures

The specimens were prepared from duralumin LY12, 30 mm in diameter. Table I gives the chemical composition of the alloy used in the experiments.

The experimental investigation was carried out on a continuous drive friction welding machine C25 with an electric field producing apparatus. The welding parameters, such as welding pressure, rotation speed, torque and axial burn-off length, can be monitored and controlled in real time during the friction welding process.

TABLE I Chemical composition of the alloy used in the experiments (wt%)

Cu	Mg	Mn	Fe	Zn	Ti	Si	Al
4.30	1.44	0.82	0.29	0.05	0.06	0.13	Balance

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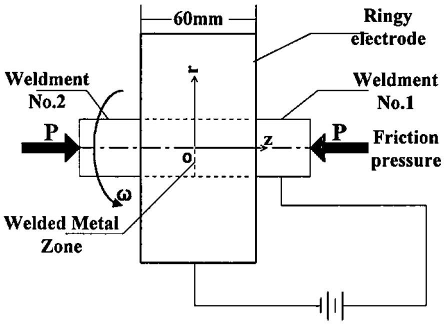


Figure 1 Schematic diagram of the experimental arrangement used in the electrostatic field.

The specimens given above were welded both with and without applying an external electric field. In the welding process, the welded material was connected to the anode of high voltage power supply that can apply constant voltage ($U = 6$ kV), and a copper ring was linked to the cathode. The air gap between the ring electrode and the specimen is 10 mm, as shown in Fig. 1. The intensity of electric field acted on the weldments can be calculated to be 7.8 kV/cm. The welding parameters used in the experiments are given in Table II. We braked the rotating shaft of the welding machine at different times for specimens No. 1 to No. 8, and then cooled the joints by spraying with liquid nitrogen and the as-welded microstructure can be frozen in. The specimens are sectioned into two pieces along the axis after welding. One is used for microstructure analysis, and the other for the hardness test. Additionally, five specimens have been welded both with ($E = 7.8$ kV/cm) and without the external electric field respectively for the average torsion strength test.

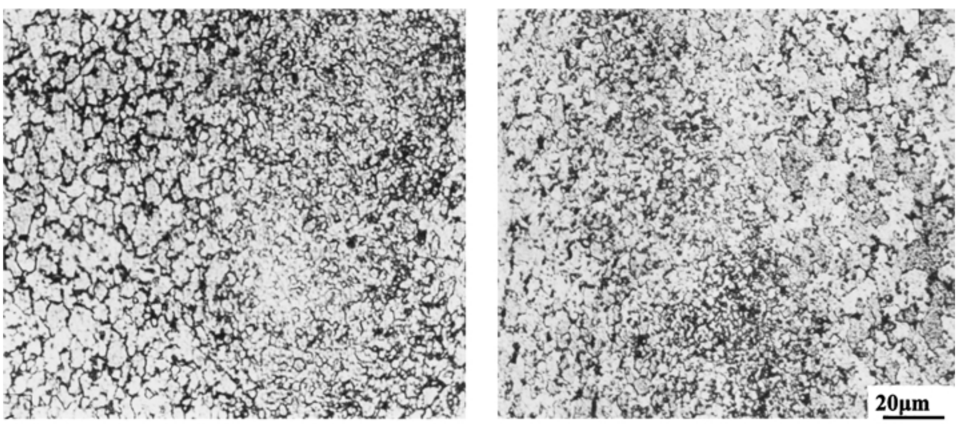
The microstructure were observed by a Newphoto-II optical microscopy. Hardness and torsion strength analyses were performed with a HX-1000 sclerometer and a NJ-150B torsion test machine respectively.

3. Experimental results

Fig. 2 gives the microstructures in the DRZ (dynamic recrystallization zone) of the friction welded joint of duralumin LY12 both with (Fig. 2a) and without (Fig. 2b) the electric field. Figs 3 and 4 show the electric field effects on the grain size (d) and the aspect ratio d_r/d_z of the grains respectively, which measured by the mean linear intercept. Because the deformation extent and deformation rate near and in the WMZ (weld metal zone) are greater than those in the DRZ, the extra fine equiaxed grains are located in WMZ and the average equivalent diameter of grains in this zone, ranging from 1 μm to 2 μm, is less than that in the DRZ. Under the external electric field, the grain size in the WMZ increases and the grain size in the DRZ decreases. Meanwhile, the ratio of d_r/d_z is reduced, which means the grains become more equiaxed along the axial direction in the WMZ and the DRZ.

TABLE II Friction welding parameters and intensity of the electric field

Specimens	Intensity of electrical field E (kV/cm)	Friction pressure P_1 (MPa)	Forging pressure P_2 (MPa)	Friction time t_1 (s)	Forging time t_2 (s)	Rotation speed N (r/min)
1	0	1.2	1.2	4.0	0	1450
2	7.8	1.2	1.2	4.0	0	1450
3	0	1.8	1.8	4.0	0	1450
4	7.8	1.8	1.8	4.0	0	1450
5	7.8	1.8	1.8	2.0	0	1450
6	7.8	1.8	1.8	6.0	0	1450
7	0	2.4	2.4	4.0	0	1450
8	7.8	2.4	2.4	4.0	0	1450
9	0	1.8	2.7	4.0	6	1450
10	7.8	1.8	2.7	4.0	6	1450



(a) (b)

Figure 2 Influence of the external electric field on the microstructure of the friction welded joint of duralumin LY12. (a) $P_1 = 1.8$ MPa, $t_1 = 4$ s, $E = 7.8$ kV/cm and (b) $P_1 = 1.8$ MPa, $t_1 = 4$ s, $E = 0$ kV/cm.

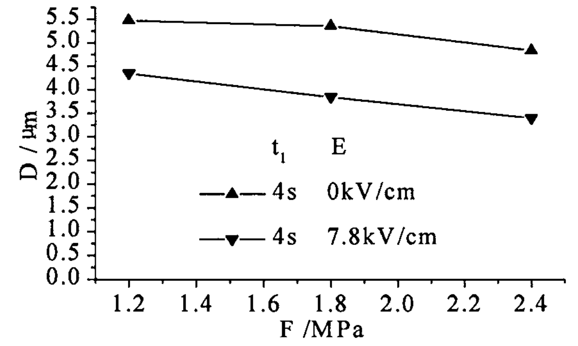


Figure 3 Effect of the friction pressure on the average equivalent diameter (D) of the grain in the DRZ.

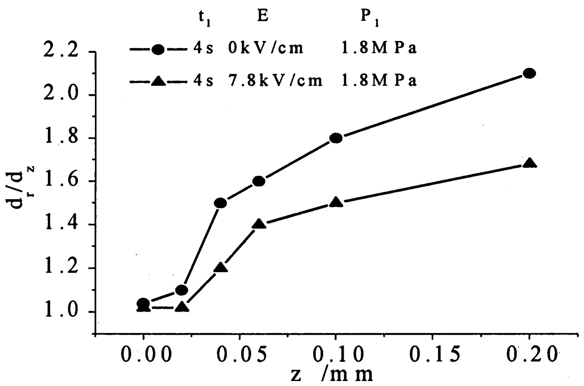


Figure 4 Effect of the external electric field on the aspect ratio (d_r/d_z) of grains and its distribution along the axial direction.

Fig. 5 shows the influences of the welding parameters and the electric field intensity on the total width of the DRZ and the WMZ of the welded joint and its distribution along the radial direction. In Figs 4 and 5, r represents the distance from the center of the specimen along the radial direction. Under different welding conditions, two kinds of the recrystallization zone (including the DRZ and the WMZ) on the welded joint can be observed. One is that the total width of the DRZ and the WMZ remains basically constant in the zone where $r \leq 3$ mm, and decreases to 0.4 mm with the increase of the radius till $r \approx 10$ mm. The other is that the width of the DRZ and WMZ increases with the increase of the radius in the zone where $r \leq 3$ mm, and also decreases to 0.4 mm with the increase of the radius till $r \approx 10$ mm. The difference resulted from the variation of the pressure and the electric field intensity.

When a higher friction pressure is employed, the total width of the recrystallization zone (including the DRZ and the WMZ) increases by 10 to 30 percent due to the electric field. When the middle friction pressure is used, the electric field effect not only results in obvious widening of the recrystallization zone, but also leads to the change of its radial distribution state. The width of the recrystallization zone becomes homogenous along the radial direction. On the other hand, under the lower friction pressure, the electric field hardly influences the width and the distribution of the recrystallization zone.

Fig. 6 presents the influences of the welding parameters and the external electric field on the average Vickers hardness distribution in the weld metal zone (WMZ) along the radial direction. When the lower friction welding pressure is applied, the hardness is lower in the WMZ at the radius between 2 mm and 6 mm than that in any other region, while the hardness changes only a little in the WMZ under the higher friction pressure. However, no matter what kind of the friction pressure is applied, the hardness shows an increasing tendency along the radial direction of the welded joints in the presence of the electric field, and its distribution becomes more even than that in absence of the electric field.

Fig. 7 shows the influence of the electric field on the average Vickers hardness distribution of the welded joint along the axial direction at different radii. Here, z is the distance from the weld line along the axial direction. The hardness on the weld line is the greatest along the axial direction, which results from the extra fine grain existing in this zone. In addition, the external electric field also leads to a more even hardness distribution along the axial direction. Moreover, there is more uniform hardness distribution along the axial direction near the outer circle zone of the welded joint than that near the axial line zone of the welded joint in the presence of the electric field.

Table III gives the torsion strength test results of the friction welded joints of duralumin LY12 both with and without the external static electric field. The increase

TABLE III Torsion properties of the welded joint both with and without the electric field

Specimens	Average yielding torsion stress τ_s (MPa)	Average torsion fracture stress τ_b (MPa)	Average torsion angle ω
9	263	332	102°
10	271	337	116°

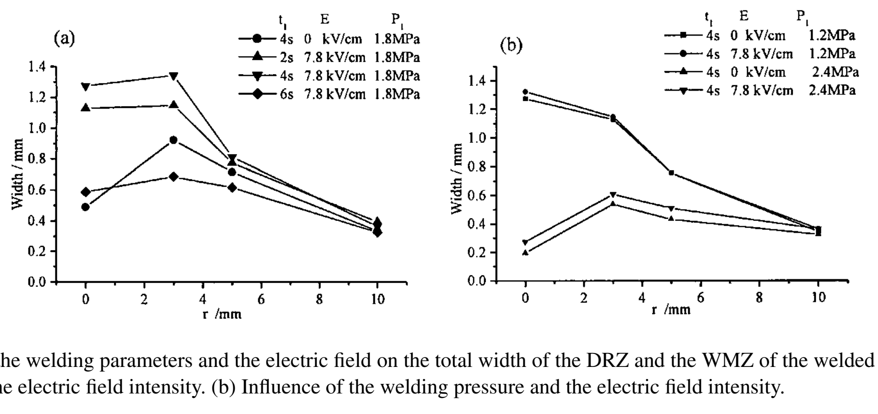
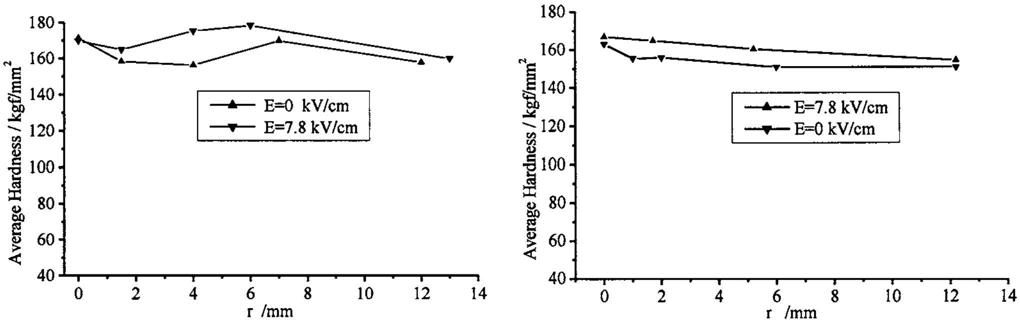
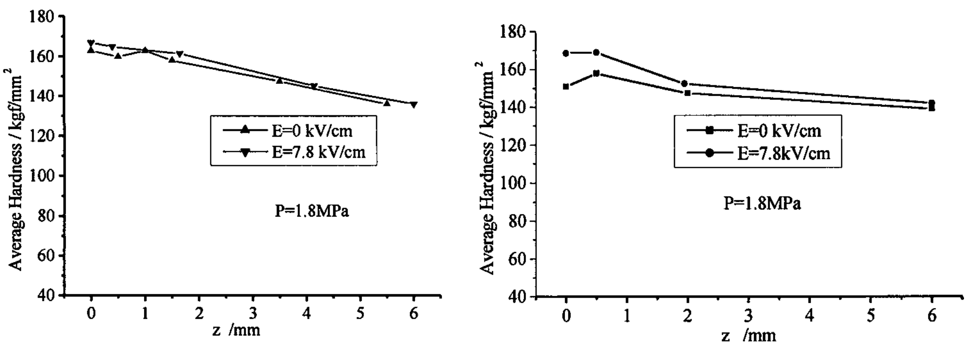


Figure 5 Influence of the welding parameters and the electric field on the total width of the DRZ and the WMZ of the welded joint. (a) Influence of the welding time and the electric field intensity. (b) Influence of the welding pressure and the electric field intensity.



(a) (b)

Figure 6 Influence of the welding parameters and the electric field on the average Vickers hardness distribution in the WMZ along the radial direction. (a) $P = 1.2$ MPa and (b) $P = 1.8$ MPa.



(a) (b)

Figure 7 Influence of the welding parameters and the electric field on the average Vickers hardness distribution of the welded joint along the axial direction. (a) $r = 0$ mm and (b) $r = 14.45$ mm.

of the average torsion angle was obtained by applying an external electric field, and the yielding torsion stress and torsion fracture stress show a little increase. It may be concluded that the friction weld metal zone of duralumin LY12 possesses a higher torsion ductility without sacrifice of the torsion strength under the electric field parameters adopted in this paper.

4. Discussions

During the friction welding process, dynamic recrystallization takes place repeatedly near and in the weld metal zone, which increases the grain boundary sliding ability. Therefore, the plastic deformation near and in the weld metal zone becomes more even. The previous research work suggested that the applied static electric field enhances the thermal and solute diffusion process, and significantly increases the ability of grain boundary sliding coupled with the diffusion process [1–4]. Owing to the influence of the static electrical field on the lattice defects (vacancies or dislocations), charged defects may occur. The applied electric filed creates a charged surface layer in metallic materials and an interaction of the surface charge with the charged defects, especially vacancies. As they approach the specimen surface, an additional defect flux will be created, which in turn governs dislocation climb and subgrain formation and coalescence. This could accelerate the nucleation of dynamic recrystallization grains, and as a result, lead to reducing the grain size.

So far, no theoretical analyses have been reported on the mechanisms, by which the electric field influences the microstructure and properties of the welded joint during the friction welding process. It is expected that vacancies and atomic mobility play roles in the process. Therefore, in the case of applying an electric field, the thermodynamic conditions of the recrystallization near and in the weld metal zone during the friction welding process can be achieved more easily. As a result, the external electric field distinctly widens the recrystallization zone (including the DRZ and the WMZ), promotes the equiaxed characteristic of the grains and decreases the microstructure differences along the axial and radial directions.

5. Conclusions

1. Under the external electric field, the recrystallization grain size in the DRZ decreases, the number of the equiaxed grains in the WMZ and the DRZ increases, the equiaxed characteristics of the recrystallization grain in the DRZ are enhanced, and the microstructure difference along the axial direction decreases.

2. When the higher friction pressure is applied, the recrystallization zone (including the DRZ and the WMZ) increases by 10–30% due to the electric field. When the middle friction pressure is used, the electric field effect not only results in widening of the recrystallization zone, but also leads to the more uniform width of the recrystallization zone along the radial direction. Under the lower friction pressure, the electric field scarcely influences the width and distribution of the recrystallization zone.

3. The hardness of the friction welded joints increases in the presence of the electric field, and its distribution becomes more uniform along the radial and axial direction than in absence of the electric field.

4. The weld metal zone of the friction welded joint shows higher torsion ductility with the external electric field than that in absence of the electric field.

Acknowledgments

This research was financially supported by the National Natural Science Foundation of China under Grant No. 50005017.

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Received 4 June
and accepted 24 December 2002