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Dynamic evolution of grain structure and micro-texture along a welding path of aluminum alloy profiles extruded by porthole dies

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ABSTRACT

The solid state welding process during porthole die extrusion of hollow structure aluminum alloy profiles is very important since it directly determines the microstructure and mechanical properties of welding seams in extruded profiles. In this study, the grain structure, special grain boundary and micro-texture along the welding path of an aluminum alloy profile were characterized, and the relation between the microstructure and mechanical properties of the welding seam was revealed. It was found that, along the welding path, the fine equiaxed grains around the welding line are elongated along extrusion direction under the combined action of shearing and compression, then, the elongated grains grow into the strip-shaped coarse grains by means of grain boundary migration, and finally, some strip-shaped coarse grains evolve into the fine equiaxed grains by means of continuous dynamic recrystallization and geometric dynamic recrystallization. Along the welding path, the fraction of special grain boundaries firstly increases and then decreases, while the fraction of low angle grain boundaries increases continually. The strong {111} fiber is formed in the zone near the surface of bridge, and it transforms into the very strong shear-type texture consisting of A^*_1 and A^*_2 components at the beginning stage of extrusion welding. Then, these shear-type texture components transform into the strong goss and copper components. Finally, the goss and copper components weaken and the weak cube texture appears in the welding zone of the extruded profile. It was also found that the increase of the low angle grain boundaries and the decrease of the average grain size in welding zone contribute to the improvement of harness, strength and fracture strain, while the existence of the strip-shaped coarse grains and different types of textures in welding zone is adverse for the improvement of welding quality.

1. Introduction

Porthole die extrusion process has been widely used to produce various kinds of hollow structure aluminum alloy profiles [1,2]. In this process, the preheated aluminum alloy billet is split into several separate streams by bridges, and then the separate streams are joined together in the welding chamber. Finally, the rejoined metal flows out of the lower die bearing and forms welding seams in extruded profiles. These welding seams are usually the weakest parts of aluminum alloy profiles, and failure mostly occurs at welding seams in the process of mechanical properties testing [3–5]. Therefore, improving the welding quality of welding seams in aluminum alloy profiles is of great importance.

Same as some advanced solid state joining technologies, such as the friction stir welding [6], linear friction welding [7] and diffusion welding [8], etc., the extrusion welding is also a solid state bonding process. The prediction of welding seams quality is the major concern for all the solid state bonding technologies. Currently, the welding quality of solid state welding seams is predicted mainly by using welding criteria [5,9–15], artificial neural network [16,17], response surface methodology [17], and physical simulation [18–23], etc.. However, most of these researches mainly focused on the prediction of the bonding degree of welding seams, that is, estimating whether the atomic bonding on the bonding interface is realized or not. In fact, even though the atomic bonding is realized on a bonding interface, the metal in the welding zone usually has the particular microstructure different from the other zones since it experiences the special thermal and mechanical history. Therefore, the mechanical properties of the metal in the welding zone are usually different from those in the other zones. This phenomenon is very common in the friction stir welding [24,25], linear friction welding [26] and accumulative roll bonding [27]. Of course, the porthole die extrusion is no exception too. Therefore, in order to predict the welding quality of porthole die extruded profiles, not only the bonding degree of the bonding interface needs to be

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Table 1
Chemical compositions of the as-homogenized AA6063 aluminum alloy.

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Ni	Al
(wt%)	0.3942	0.1221	0.0844	0.0063	0.5563	0.0035	0.0085	0.0103	0.0048	Bal.

investigated, but also the microstructural evolution of the metal in the welding zone needs to be studied even.

Extrusion welding is a hot deformation process involving solid state interface bonding. In the process of hot deformation, there is a competition between strain hardening and dynamic softening of aluminum alloy materials [28]. Strain hardening occurs when plastic deformation gives rise to the increase of dislocation density by means of the accumulating and pilling up of dislocations at second phase particles and boundaries of grains as well as subgrains [29]. Dynamic softening takes place when an elevated temperature causes the decrease of dislocation density by means of the climbing, cross slipping and annihilating of dislocations. Since aluminum alloys have high stacking fault energy, during their hot deformation, dynamic recovery, continuous dynamic recrystallization and geometric dynamic recrystallization are their main softening mechanisms [30,31]. After deformation, static recovery and static recrystallization may also occur at a high temperature [32]. It should be noticed that extrusion welding not only involves the strain hardening and dynamic softening, but also involves solid state interface bonding. Therefore, the microstructural evolution in extrusion welding process becomes very complex.

As we all known, metal materials' performance is closely related to their microstructure. Grain and subgrain structures affect the materials' strength and toughness. Texture usually gives rise to the anisotropy of materials' performance. Special grain boundary may influence the intergranular corrosion resistance of materials. Therefore, investigating the microstructural evolution during the hot extrusion of aluminum alloy profiles is very important. Güzel et al. [29] and Kayser et al. [33] investigated the grain structure evolution in the hot extrusion process of rods. Fan et al. [34] studied the grain structure and texture evolution in the porthole die extrusion process of a multi-port flat tube. However, the crucial process in porthole die extrusion is the extrusion welding. The grain structure and texture evolution in welding zone is the key factor to determine the welding quality of extruded profiles. Unfortunately, the dynamic evolution of grain structure and micro-texture along the welding path of aluminum alloy profiles extruded by porthole dies has been not clarified so far.

In conclusion, extrusion welding is a complex solid state welding process involving thermal, mechanical and microstructural evolution. Predicting the welding quality of extruded profiles should take both the bonding degree and microstructure into consideration. On the premise of achieving atomic bonding on the bonding interface, the microstructure of the metal in the welding zone is crucial for the welding quality of extruded profiles. For this reason, this study focuses on the investigation of the evolution of grain structure, special grain boundary and micro-texture in welding zone, and the analysis of mechanical properties of the metal in different positions of welding zone. Firstly, an extrusion experiment was carried out and the remaining metal was separated from die cavity. Then, optical microscopy was used to observe the metal flow line and determine the welding path. After that, the evolution of grain structure, special grain boundary and micro-texture along the welding path was studied by using electron backscattered diffraction (EBSD) technology. Finally, the micro-hardness and tensile properties were measured, and the relation between the microstructure and mechanical properties of the welding seam was discussed.

2. Experimental methods and procedure

2.1. Materials preparation

Before extrusion experiment, the as-cast billets of AA6063 aluminum alloy with the dimensions of Ø152 mm ×450 mm were prepared and homogenized at 530 °C for 14 h and then cooled down to the room temperature in the air. The chemical compositions of AA6063 aluminum alloy shown in Table 1 were obtained by using direct reading spectrometer. In addition, the optical microstructure of the original as-homogenized billets is shown in Fig. 1. The calculated average grain size is around 120 μm according to ASTM: E112-13.

2.2. Extrusion die and extrusion experiment

The experimental extrusion die was designed in a modular way. It consists of an upper die, a bridge and a lower die, as shown in Fig. 2(a). The height h of the welding chamber was designed as 35 mm. The dimensions of the extruded profile's cross-section are 80 mm in width and 12 mm in thickness. Fig. 2(b) gives the dimensions of the assembled die in detail. The extrusion experiment was performed on a 16 MN extrusion press. The temperatures of container, extrusion die and billet were set as 460 °C, 450 °C and 500 °C, respectively, and the ram speed was set to be 4.0 mm/s. After extrusion, the extrusion die and the remaining metal were removed from the extrusion press and cooled down to the room temperature in the air.

2.3. Sampling and characterization

After the extrusion die and the remaining metal were cooled down to the room temperature, the remaining metal was separated from die cavity and then divided into two symmetrical parts along XY plane by wire-electrode cutting. Fig. 3(a) shows the shape of the metal in the die cavity and the position of the XY plane. Fig. 3(b) is a photo of one half of the metal cut along XY plane.

The longitudinal section (XY plane in Fig. 3(a)) of the cut metal was observed by optical microscopy, and some special zones on the long-

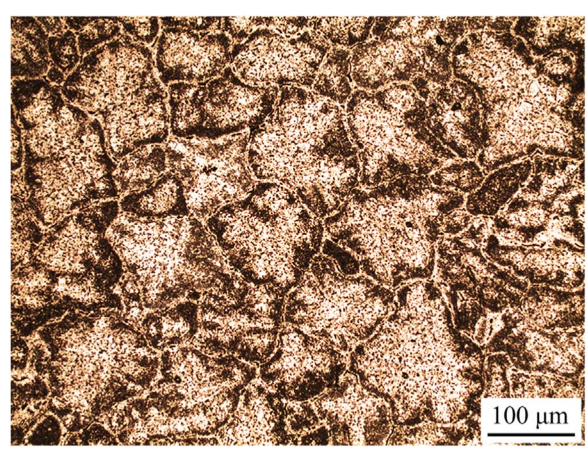

Fig. 1. Optical microstructure of the original as-homogenized AA6063 aluminum alloy.