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Investigation of interface evolution, microstructure and mechanical properties of solid-state bonding seams in hot extrusion process of aluminum alloy profiles

Junquan Yu, Guoqun Zhao*, Liang Chen

Key Laboratory for Liquid–Solid Structural Evolution and Processing of Materials (Ministry of Education), Shandong University, Jinan, Shandong 250061, PR China

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ABSTRACT

Solid-state bonding is an important problem in hot extrusion process of aluminum alloy profiles, especially for hollow section profiles. Predicting and decreasing the length of transverse weld seam (T-seam), improving the solid-state bonding degree and controlling microstructure of longitudinal weld seam (L-seam) are major concerns. In this work, a set of porthole extrusion dies with different shapes of legs (pointed and square) and depths of welding chambers were designed and manufactured. A series of extrusion experiments for different die structure parameters were performed, and microstructure observations, tensile tests and fracture feature analyses for the extruded profiles were conducted. The influences of the shapes of legs and the depths of welding chambers on the evolution and the length of T-seams and on the formation, microstructure and mechanical properties of L-seams were respectively investigated by means of experiment and numerical simulation. The distribution law of the ratio of pressure to material flow stress, p/σ, and the material flow behavior in welding plane were studied by using numerical simulation method. The results showed that the profiles extruded by the dies with pointed legs have single-convex T-seams and straight L-seams on their cross sections, and their T-seams are relatively shorter but their ductility is relatively inferior. While, the profiles extruded by the dies with square legs have double-convex T-seams and cross-shaped L-seams, their ductility is relatively superior but their T-seams are longer. With the increase of the depth of welding chamber, the ductility of the extruded profiles is increased, but the lengths of T-seams are almost invariable. In addition, it was found from numerical simulation results that, in the welding plane, the deforming material with a higher flow velocity has a lower value of p/σ, and vice versa. It was concluded that an effective welding zone should exist in the welding plane, and the deforming material only in this effective welding zone can flow into the extrusion die bearing to form an L-seam in extruded profile.

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1. Introduction

Due to the advantages of recyclability, light-weight and excellent mechanical properties, aluminum alloy profiles play an important role in many fields, such as architecture, railway transportation, engineering structure and aerospace. As a typical plastic deformation process with high productivity, hot extrusion process has been widely used to produce a variety of aluminum alloy profiles. Generally speaking, the cross-section shapes of profiles can be divided into two main categories: solid and hollow sections. With the development of industry, the demand for the profiles with large cross-section, thin wall, and multi-cavity is increasing significantly. For the purpose of high productivity, this kind of aluminum alloy profiles are usually extruded by using porthole dies.

In the extrusion process of hollow section profiles with porthole dies, the formation of longitudinal weld seam (L-seam) is an inevitable problem. In this process, a preheated aluminum alloy billet is loaded into the extrusion container, and upset under the pressure of ram. When the metal is extruded into portholes, it is split into several separate streams by bridges, and then the streams are rejoined together in welding chamber. Finally, the rejoined metal breaks through the bearing of lower die and forms a profile with L-seams inside. In general, the L-seams are the weakest areas of the profile. Kim et al. (2002) found that the failure mostly occurs along or around the L-seams when the profile is subjected to

* Corresponding author. Fax: +86 0 53188392811.
E-mail addresses: yujunquansdu@163.com (J. Yu), zhaogq@sdu.edu.cn (G. Zhao), chenliang@sdu.edu.cn (L. Chen).

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severe internal pressure or expansion. Since hollow section profiles extruded by using the porthole dies always have L-seams, improving solid-state bonding degree and controlling microstructure of L-seams becomes an important issue for practical production.

Another kind of weld seam in profile extrusion process is the transverse weld seam (T-seam), which is formed during continuous extrusion. When an old billet in the container is extruded to a certain degree, since the remained old billet (butt scrap) in container usually contains many inclusions, it should be sheared off to avoid back-end defect. After shearing, another new billet is put into the container and the extrusion process is continued again. As the extrusion proceeding, the interface between the old billet and the new billet gradually flows through die cavity and bearing. As a result, T-seams are gradually formed inside the extruded profile. Nanninga et al. (2010) found that T-seams usually have inferior mechanical properties since they are contaminated by oxides and dust. In practice, most of profiles are extruded by means of continuous extrusion. Consequently, predicting and reducing the lengths of T-seams are of great importance.

The formations of the above L-seams and T-seams in hot extrusion process are all belonged to solid-state bonding process, which means that only solid-phase metals bond together and no liquid-phase metals appear in the process of bonding. It was reported by Gould (2001) that there are many asperities on the solid-phase metal's surface, and the precondition for a sound seam of solid-state bonding is that the asperities on the interface of solid-phase metals are collapsed to create a micro-level intimate contact. Main mechanisms for creating intimate contact include the surface plastic deformation mechanism and creep or surface diffusion mechanism. The surface plastic deformation mechanism means that an intimate contact is created by means of plastic deformation of the asperities on interfaces, which occurs at the condition that the equivalent stress of the contact surfaces reaches to the yield stress of material. While, the creep or surface diffusion mechanisms mean that the asperities on the interface are gradually collapsed by means of creep or diffusion, and an intimate contact occurs when the contact interface has a relative lower pressure but longer contact time.

In aluminum alloy extrusion process, since the metal streams are subjected to high pressure and velocity when they flow through welding chamber and form L-seams and T-seams, the formation mechanism of these weld seams tends to the surface plastic deformation mechanism. Bay (1983) demonstrated that during the formation of weld seams, the breaking up of surface films and the exposing of virgin materials by means of plastic deformation are necessary for a sound bonding. In order to predict the bonding degree of weld seams of aluminum alloy profile, several welding criteria have been proposed based on the pressure in welding plane. Akeret (1972) proposed the maximum pressure criterion, which is stated as that the maximum pressure inside the welding chamber must exceed a critical limit for a sound weld seam. Plata and Piwnik (2000) proposed the pressure–time criterion, which is stated as that a sound weld seam can be formed once the integral of ratio of contact pressure to material flow stress on time on welding surface exceeds a critical value. Donati and Tomesani (2004) proposed the pressure–time–flow criterion, which is stated as that a sound weld seam can be formed once the integral of ratio of contact pressure to material flow stress on all possible welding paths on welding surface exceeds a critical value. Although the above criteria can predict the bonding degree of weld seams in a way, den Bakker et al. (2014) found that in some special cases, for example, when the gas pocket appeared during extrusion, the above criteria can not predict the bonding degree of weld seams. Therefore, the fundamental experimental investigation on the evolution of T-seam and the formation of L-seam is necessary for establishment of more accurate welding criteria.

Optimization of extrusion die structures is one the most effective approaches to improve the quality of L-seams. The depths and volumes of welding chambers and the shapes of legs (square or pointed) have significant influence on the material flow behavior and L-seams quality in porthole die extrusion process. Donati et al. (2007) found that increasing the depth or enlarging the volume of welding chamber is helpful to gain sound weld seams. Valberg et al. (1995) found that with the increase of the depth of welding chamber, the bonding state of weld seams inside profile can vary from no welding to partial welding, complete but unsound welding and sound welding. In addition, Valberg (2002) found that compared to the square leg (a leg with square rear end), the pointed leg (a leg with pointed rear end) can reduce the areas of dead zone behind the leg, and thereby promote to obtain a complete welding. However, when the weld seams of profiles extruded by using the pointed and square legs are all in complete welding state, their welding qualities or performances are still not clarified or figured out.

In order to study the evolution of T-seams and predict their length, many researches based on numerical simulation have been conducted. Li et al. (2003) revealed the formation of T-seams and material flow behavior in aluminum extrusion processes. Based on the Deform-2D software and a new algorithm, Mahmoodkhani et al. (2014) tracked the boundary layer of T-seams and predicted the clad layer thicknesses. In addition, Reggiani et al. (2013) investigated the evolution of the T-seams inside industrial multi-profiles by using the HyperXtrude software, and found that numerical and experimental results are in a good agreement. Chen et al. (2015) also investigated the effects of ram speed on the evolution of T-seams extruded by pyramid die by using the HyperXtrude software and found that the length of T-seams is reduced at higher ram velocity. However, the study on the effects of different depths of welding chambers and shapes of legs on evolution and length of T-seams are still not reported.

In conclusion, although many research works have been done to investigate the L-seams and T-seams of profile in hot extrusion process of aluminum alloy, there are still two critical problems needed to be further investigated and clarified. Firstly, most of previous works only focused on the L-seams and ignored the T-seams. Although the profile with T-seams is discarded in actual production, the investigation on the evolution of T-seams is not only helpful to accurately determine the length of T-seams but also to understand the material flow behavior and the formation process of L-seams in continuous extrusion. Thus, it is necessary to comprehensively investigate both T-seams and L-seams in aluminum profile extrusion processes. Secondly, there is still lack of a systemic investigation on the influence of the depths of welding chambers and the shapes of legs on the evolution and the length of T-seams and on the formation, microstructure and mechanical properties of L-seams. This investigation is a key foundation for welding criteria establishment and seams quality prediction.

In this work, a comprehensive investigation on weld seams of aluminum alloy profile in hot extrusion process was conducted. A set of modular porthole extrusion dies with different shapes of legs and depths of welding chamber were designed and manufactured. Extrusion experiments were performed by using modular extrusion dies with different structure parameters. The microstructure observations, tensile tests and fracture feature analyses for the extruded profiles were carried out. Influences of the shapes of legs and the depths of welding chambers on the evolution and the length of T-seams and on the formation, microstructure and mechanical properties of L-seams were investigated by using experiment and numerical simulation. The distribution law of the ratio of pressure to material flow stress, p/σ, and the material flow behavior in welding plane were also studied by using numerical simulation.

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