Materials Characterization 138 (2018) 56–66

Contents lists available at ScienceDirect

Materials Characterization

journal homepage: www.elsevier.com/locate/matchar

Interfacial structure and bonding mechanism of weld seams during porthole die extrusion of aluminum alloy profiles

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ARTICLE INFO

Keywords:
Porthole die extrusion
Interfacial structure
Interfacial bonding mechanism
Micro-void closure
Interfacial grain boundary migration

ABSTRACT

Fine nanostructures of bonding interfaces of weld seams formed by porthole die extrusion in the absence/presence of a gas-pocket behind the bridge of the extrusion die were systematically studied to understand the underlying interfacial bonding mechanisms. Interfacial grain boundaries, nanoscale amorphous layers, and three kinds of new interfacial structures were found. Specifically, it was found that, in the absence of a gas-pocket behind the bridge, there are two distinctly different interfacial structures. For the first kind of bonding interface, interfacial grain boundaries exist in contact areas and micro-voids exist in non-contact areas. For the second kind of bonding interface, there are no interfacial grain boundaries in contact areas and only nanoscale micro-voids exist in non-contact areas. In the presence of a gas-pocket behind the bridge, nanoscale voids and amorphous layers exist at the bonding interface. It was also found that the formation of gas-pockets can be avoided by increasing the depth of the welding chamber, and the increase of the welding chamber's depth and extrusion speed also contributes to the volume reduction of micro-voids and the migration of grain boundaries at the bonding interface, so as to improve the welding quality of weld seams. Based on the experimental findings, two interfacial bonding mechanisms corresponding to the absence/presence of a gas-pocket are proposed. The specific behavior of micro-asperities contact, micro-voids closure, oxide films breaking and interfacial grain boundaries migration are described, and the solid-state bonding process during porthole die extrusion is revealed from the micro-nano scales.

1. Introduction

With the rapid development of industrial technology, the global challenges, such as energy, resources and environment, have become increasingly prominent. Therefore, there is a strong preference for high performance lightweight structural components, such as large scale and thin-walled aluminum alloy hollow profiles with multiple cavities [1,2], as used in high-speed trains, buildings, boats and ships, and engineering structures. Usually, this kind of lightweight hollow profiles is manufactured by using the porthole die extrusion process. A set of typical porthole dies are shown in Fig. 1(a). During porthole die extrusion, a billet is split into several metal streams in extrusion dies' portholes and then joined in a welding chamber. As a result, there are usually many weld seams in large scale and thin-walled aluminum alloy hollow profiles with multiple cavities, as shown in Fig. 1(b), where the red arrows indicate the positions of weld seams. Welding quality is the pivotal factor in determining the performance of profiles extruded by porthole dies [3,4]. However, since the formation process of weld seams is very complex and involves many influencing factors, such as welding path, stress and strain conditions, temperature and bonding time, it becomes a challenging problem to accurately predict and control welding quality of weld seams [5,6]. In fact, as some solid-state joining technologies, such as friction stir welding [7,8], linear friction welding [9] and superplastic forming/diffusion bonding [10], etc., the porthole die extrusion process is also a solid-state bonding process. For all solid-state bonding technologies, interfacial structures and interfacial bonding mechanisms [11–13] of weld seams are the common concerns of researchers, since these two issues are the foundation for accurately predicting and controlling the welding quality of weld seams [14–18].

In the last few decades, many studies have been carried out to investigate welding quality of profiles extruded by the use of porthole dies. It has been found that extrusion die geometry has a significant influence on the welding quality of extruded profiles. Very shallow welding chambers will result in the formation of macro defects in extruded profiles [19,20]. Increasing the depth of welding chambers can eliminate macro defects, but may lead to the formation of unsound weld seams with clearly visible bonding interfaces [20]. A further increase in

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https://doi.org/10.1016/j.matchar.2018.01.052
Received 20 July 2017; Received in revised form 10 December 2017; Accepted 31 January 2018
Available online 02 February 2018

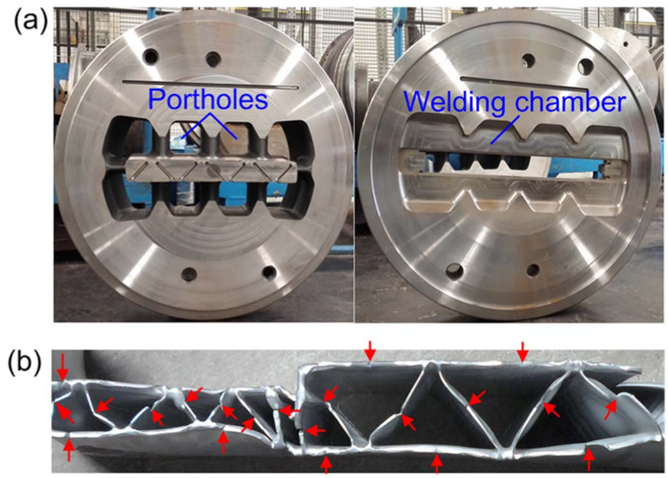

Fig. 1. (a) A set of typical porthole dies, (b) the positions of weld seams in a profile extruded by a porthole die.

the depth of welding chambers can completely eliminate bonding interfaces and obtain sound weld seams [20]. Furthermore, increasing the volume of welding chambers also contributes to the improvement of welding quality [21]. It has also been found that the effect of extrusion speed, temperature, and extrusion ratio on welding quality is complex. Within a certain range, increasing extrusion speed, temperature and extrusion ratio contribute to the improvement of welding quality [22,23]. However, beyond this range, the increase of extrusion speed, temperature and extrusion ratio will result in a decline of welding quality [23,24]. In addition, researchers have also investigated the dynamic evolution of grain structure and micro-texture along the welding paths of an AA1100 aluminum alloy [25], an AA6063 aluminum alloy [26] and an Al-Zn-Mg alloy [27] profiles during porthole die extrusion, and it was found that the size and morphology of grains, the micro-texture and the mechanical properties of the metal in the welding areas are significantly different along the welding paths. The difference of grain morphology and orientation between the welded and non-welded regions has a significant effect on the mechanical properties of the extruded profiles [28]. However, it should be pointed out that, although many studies have been carried out to investigate the welding quality of profiles extruded by porthole dies, the majority of previous studies mainly focused on grain structure and mechanical properties of weld seams [4,21–25,29–31], and investigations of interfacial structures and interfacial bonding mechanisms of weld seams are almost absent. The fine nanostructures of bonding interfaces can not only directly present the bonding degree of bonding interfaces from the atomic scale, but also can reveal the bonding mechanisms of the solid-state bonding interfaces. Therefore, further deep investigations of the fine nanostructures of bonding interfaces of weld seams are clearly required.

The accurate prediction of welding quality can provide the basis for the design of extrusion dies and the definition of process parameters. Some welding criteria have been proposed to predict welding quality of profiles extruded by porthole dies. In earlier years, the maximum pressure inside welding chambers was used to judge the quality of weld seams in extruded profiles [32]. In recent years, the integral of the ratio of contact pressure to material flow stress on time on welding surface (Q criterion) [33], the integral of the ratio of contact pressure to material flow stress on all possible welding paths on welding surface (K criterion) [18], and the dimensionless bonding criterion related to stress triaxiality, effective strain rate, temperature and contact time (J criterion) [20], have been used to predict welding quality. Additionally, some basic solid-state bonding tests, such as the uniaxial hot compression tests [31,34,35] and flat rolling experiments [36] have also been used to predict welding quality. However, all the welding criteria and some other equations currently used to predict the welding quality of extruded profiles are phenomenological. In order to achieve an accurate prediction of welding quality, more accurate welding criteria should be established based on interfacial bonding mechanisms in the porthole die extrusion process. In a previous study on longitudinal weld seam defects and bonding criteria in the porthole die extrusion process of aluminum alloy profiles [20], a preliminary proposal for the extrusion bonding mechanism was made. However, this proposed extrusion bonding mechanism only takes the closure behavior of the micro-voids at bonding interfaces into consideration, and simply describes the closure behavior of micro-voids based on plastic deformation and diffusion. In another previous study on the microstructural evolution and mechanical properties of weld seams in aluminum alloy profiles extruded by a porthole die [22], the existence of micro-voids at the bonding interfaces of weld seams in the absence of a gas-pocket behind the bridge of the extrusion die was confirmed by experimental observations. However, a comparative study to reveal the fine nanostructures of bonding interfaces of weld seams formed in the absence/presence of a gas-pocket behind the bridge of the extrusion die was not carried out. Any interfacial bonding mechanisms of weld seams formed in the absence/presence of a gas-pocket were neither proposed.

In summary, since welding quality is the pivotal factor in determining the performance of the complex profiles extruded by porthole dies, achieving accurate control and prediction of welding quality becomes very important. Revealing interfacial structures and interfacial bonding mechanisms of weld seams is a foundation for achieving accurate control and prediction of welding quality. However, there are few research reports about the interfacial structures of the weld seams extruded by porthole dies, and investigations of interfacial bonding mechanisms during porthole die extrusion are still absent. Therefore, in-depth and systematic studies on interfacial structures and bonding mechanisms of weld seams during porthole die extrusion have important theoretical interest and practical significance for the manufacturing of high performance lightweight aluminum alloy hollow profiles.

In this study, by changing extrusion die geometry and process parameters during porthole dies extrusion, different kinds of Al-Mg-Si alloy weld seams were fabricated. The interfacial structures of the weld seams were systematically examined by using light optical microscopy (LOM), electron backscattered diffraction (EBSD) and transmission electron microscopy (TEM). Specifically, the fine nanostructures of the bonding interfaces were characterized by using high-resolution transmission electron microscopy (HRTEM). The influence of extrusion die geometry and process parameters on the formation processes, solid-state bonding conditions and interfacial structures of weld seams was revealed. Finally, based on the experimental findings, interfacial bonding mechanisms of weld seams during porthole die extrusion of aluminum alloy profiles are proposed.

2. Experimental Methods

In this study, the experimental material is homogenized Al-Mg-Si billets with the chemical composition (wt%) of Al-0.394Si-0.122Fe-0.084Cu-0.006Mn-0.556Mg-0.003Cr-0.009Zn-0.010Ti-0.005Ni. The experimental porthole dies are shown in Fig. 2. This kind of porthole dies consists of upper die, lower die and bridge. By altering the geometry such as the dimensions of lower dies and bridges as well as process parameters such as extrusion temperature and speed, profiles with different kinds of welding defects can be obtained. In this work, through many attempts with different dimensions of lower dies and bridges, extrusion temperatures and speeds, four representative experiments are selected, as shown in Table 1. For extrusion experiments No. 1 and No. 2, the depth h of welding chambers is 15 mm, and the cross-section size of extruded profiles is 80.0 mm × 12.0 mm (extrusion ratio = 20.9). The temperatures of billets, extrusion dies and containers are 490 °C, 450 °C and 440 °C, respectively. The extrusion speeds of