Journal of Materials Processing Technology 237 (2016) 31–47

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Analysis of longitudinal weld seam defects and investigation of solid-state bonding criteria in porthole die 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

ARTICLE INFO

Article history:
Received 22 January 2016
Received in revised form 7 April 2016
Accepted 21 May 2016
Available online 24 May 2016

Keywords:
Aluminum alloy profile
Extrusion
Weld seam defect
Welding path
Bonding criterion

ABSTRACT

In porthole die extrusion process of aluminum alloy profiles, the formation of longitudinal weld seams (L-seams) is inevitable. Analysis of L-seam defects and investigation of solid-state bonding criteria are important issues for practical production. In this study, a set of modular porthole extrusion dies with different depths of welding chambers were designed and manufactured. The profiles extruded with different depths of welding chambers were obtained by performing extrusion experiments.The welding quality of extruded profiles was characterized by means of microstructure observation, tensile test and fracture analysis. The true stress-strain curves of homogenized AA6063 aluminum alloy with various strain rates and deformation temperatures were obtained by means of isothermal hot compression test. Three-dimensional transient numerical simulation models of the porthole die extrusion processes were established. Flow behaviors of aluminum alloy in porthole die extrusion process were investigated, and the formation processes of L-seams and their defects were revealed. The solid-state bonding processes of metal particles were traced and their welding paths were determined. Finally, based on the plastic deformation and diffusion mechanisms for closure behaviors of micro voids on contact interfaces, a new dimensionless solid-state bonding criterion related to stress triaxiality, effective strain rate, temperature and contact time was proposed. The bonding quality of L-seams of extruded profiles without any macro defect was predicted successfully by using this new criterion. In addition, it was found that the formation of a macro hole in the profile extruded with a shallow welding chamber is attributed to metal flow behavior, and does not relate to solid-state bonding process.

1. Introduction

Due to the advantages of recyclability, light-weight and excellent corrosion resistance and mechanical properties, aluminum alloy profiles play an important role in many fields, such as railway transportation, shipbuilding, automobile industry, aerospace manufacturing, electronic equipment and engineering structure. As a typical plastic deformation process, hot extrusion process has been widely used to produce various kinds of aluminum alloy profiles. With the development of industry, the hollow section profiles with large scale, thin-wall, multi-cavity and complex cross-section, as shown in Fig. 1, are drawing more and more attention and the demand for these profiles is increasing significantly. For the purpose of high productivity, this kind of aluminum alloy profiles are usually extruded by using porthole die direct extrusion process.

In porthole die extrusion process of hollow section profiles, when a preheated aluminum alloy metal is extruded into portholes, it is firstly 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 longitudinal weld seams (L-seams) inside. Owing to improper extrusion process parameter or die structure, unsound bonding may occur in the forming process of a hollow section profile. Kim et al. (2002) stated that the failure of a hollow section profile mostly occurs along or around L-seams when the profile is subjected to severe internal pressure in the practical use. Therefore, L-seams are usually the weakest areas of hollow section profiles. In practice, the welding quality of profiles with large scale, multi-cavity and complex cross-section can be detected by means of burst test. Fracture always occurs at the position where the L-seam has

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

http://dx.doi.org/10.1016/j.jmatprotec.2016.05.024
0924-0136/

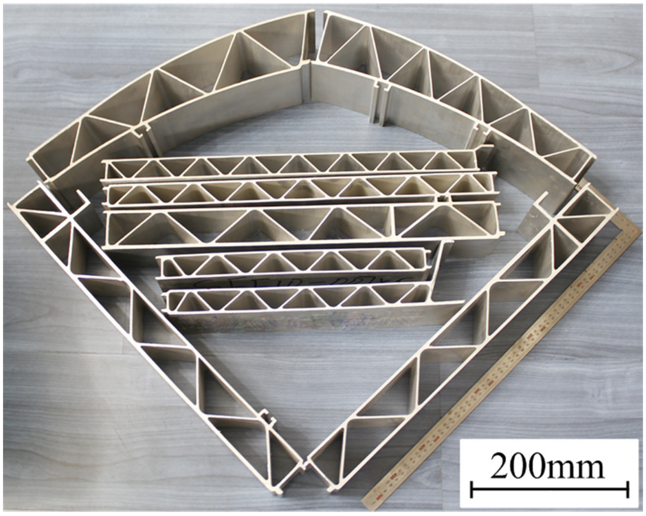

Fig. 1. Aluminum alloy profiles with large scale, thin-wall, multi-cavity and complex cross-section.

poor welding quality, as shown in Fig. 2. Consequently, investigating the formation mechanism of L-seams and their defects and establishing criterion for welding quality prediction have important theoretical significance and engineering application values for extrusion die and extrusion process design to ensure the welding quality of L-seams.

Defects of L-seams of profiles extruded by porthole dies can be classified into two categories: macro and micro defects. The macro defects refer to macro holes or gaps which are formed on unbonding surfaces. The micro defects refer to micro voids, cracks, oxide films, or other inclusions, which result in unsound bonding of metal atoms on bonding interface. In practise, defects of L-seams are mainly caused by improper extrusion die structure. Den Bakkera et al. (2014) found that a very shallow welding chamber can cause the appearance of a macro hole defect on profile's cross-section. Valberg et al. (1995) found that a relative shallow welding chamber can lead to a transition of sticking friction to sliding friction at the rear end of bridge. This transition results in the formation of free metal surfaces which are pressed into each other by classical pressure welding to form L-seams. As a result, some oxide particles may exist in L-seams. Furthermore, Donati and Tomesani (2005) found that a deep and large welding chamber contributes to the improvement of welding quality and extrusion speed limit.

In order to evaluate the welding quality of L-seams of extruded aluminum alloy profiles, researchers mainly carried out following studies.

(1) Bonding criteria. Several bonding criteria were established according to extrusion experimental results and theoretical derivation. Akeret (1972) earliest proposed the maximum pressure criterion, which is stated as that the maximum pressure inside the welding chamber must exceed a critical limit to form a sound weld seam. More recently, Plata and Piwnik (2000) proposed the pressure-time criterion (Q criterion), which is stated as that the integral of ratio of contact pressure to material flow stress on time on welding surface must exceed a critical value to obtain a sound weld seam. Finally, Donati and Tomesani (2004) proposed the pressure-time-flow criterion (K 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.

(2) Numerical simulations. In the extrusion process with a porthole die, relevant physical variables such as pressure, effective stress and metal flow velocity are important for welding quality evaluation of L-seams, and these physical variables are usually obtained by means of numerical simulation. Currently, the porthole die extrusion process is simulated mainly by using Deform software based on Lagrange algorithm or HyperXtrude software based on arbitrary Lagrange-Euler (ALE) algorithm. Based on the bonding criteria and the numerical simulation softwares mentioned above, Güley et al. (2013) studied the effect of die design on the welding quality during solid state recycling of AA6060 chips, and Chen et al. (2011) evaluated the welding quality of a complex aluminum alloy multi-cavity wallboard of high-speed train.

(3) Physical simulations. In fact, the formation of an L-seam in pothole die extrusion process is belonged to solid-state bonding process. Physical simulation means that the formation of an L-seam in porthole die extrusion process is simulated by means of some basic solid-state bonding tests, such as the uniaxial hot compression test used by Edwards et al. (2009) and the flat rolling experiment reported by Ceretti et al. (2009). By combining numerical simulation with uniaxial hot compression test, Tang et al. (2014) evaluated the weld seam quality of a micro channel tube according to the relationship of welding chamber height, hydrostatic pressure and L-seam welding strength.

Although some research has been done to investigate the L-seams' defects and the bonding criteria in porthole die extrusion process of aluminum alloy profiles, several critical problems still need to be further classified.

Firstly, there are still some problems for the evaluation method of welding quality of L-seams. Most of previous studies took the average effect of the whole bonding zone of an L-seam on profile's cross-section as a standard to evaluate the welding quality of the L-seam. Namely, only the overall effect of relevant physical quantities of all the particles in welding plane on the welding quality of an L-seam is considered. However, the recent study of Yu et al. (2016) showed that the welding quality in the whole bonding zone of an L-seam on profile's cross-section is usually variable. Since the failure is easy to originate at the weakest bonding position, the welding quality of each particle of an L-seam should be evaluated individ-

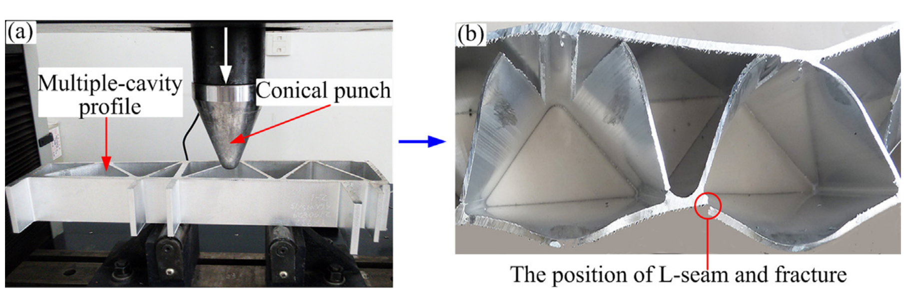

Fig. 2. Burst test for a hollow section aluminum alloy profile: (a) test equipment, (b) fracture location.