Materials Characterization 118 (2016) 468–480

Contents lists available at ScienceDirect

Materials Characterization

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

Microstructure development and texture evolution of aluminum multi-port extrusion tube during the porthole die extrusion

X.H. Fan [a,b], D. Tang [a,b,*], W.L. Fang [a,b], D.Y. Li [a,b], Y.H. Peng [a,b]

[a] State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China
[b] School of Mechanical Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China

ARTICLE INFO

Article history:
Received 12 January 2016
Received in revised form 22 May 2016
Accepted 19 June 2016
Available online 22 June 2016

Keywords:
Porthole die extrusion
Dynamic recrystallization
Texture
Solid state welding

ABSTRACT

Aluminum multi-port extrusion tube is processed by the porthole die extrusion and the internal tube walls are welded through the solid state metallurgical bonding. In order to observe the development of grains and their orientations under severe plastic deformation and solid state welding, the extrusion butt together with the die is quenched immediately after extrusion to preserve the grain structure in the processing. The forming histories of selected material points are obtained by analyzing the optical microscopy graph. The evolution of the microstructure along the forming path is characterized by electro backscattered diffraction. It is found that geometrical dynamic recrystallization happens in the process. Grains are elongated, scattered at the transition zone and shear intensive zone, and then pinched off when they are pushed out from the die orifice. The shear-type orientations are predominant at the surface layer on the longitudinal section of the tube web and have penetrated into the intermediate layer. The rolling-type orientations are formed at the central layer. Texture gradient through the thickness of the tube web is observed. And cube orientated grains are found at the seam weld region.

1. Introduction

With the advent of the climate control systems that operate at higher pressures, the demand to improve and optimize the design of aluminum multi-port extrusion (MPE) tube has become a hot spot in refrigeration and air-conditioning field. The design of aluminum MPE tube is not only to satisfy the heat transfer requirement, but also to withstand internal pressure with minimization of materials and manufacturing costs. The webs, also known as internal walls, are seam welded in a restricted height welding chamber of a high precision porthole die. They serve as the structural members in aluminum MPE tube. In the burst pressure testing, failure of the tube commonly starts at the webs [1,2]. The mechanical properties of the webs are associated with the microstructures, such as grain morphology, grain size, texture and the location of welding plane [3–5]. Hence, the understanding of the restoration and bonding mechanisms during the porthole die extrusion is of great industrial significance.

For aluminum and its alloys, the microstructures during thermomechanical deformation have been widely investigated [6–10]. Due to their high stacking fault energy, dynamic recovery is likely to happen. Dislocations move freely and annihilate each other, leading to the arrangement of the remainder into highly polygonized subgrains at elevated temperatures. In association with the dislocations, the serration of the original grain boundaries attracts much attention of the researchers [8,11–14]. Geometrical dynamic recrystallization (GDRX) has been proposed and discussed by McQueen and co-workers [11,15,16]. This phenomenon is first observed in Al-5Mg and Al-Mg2Si alloys [11] and commercial aluminum alloy [15]. According to his theory, the original grains elongate as strain increases but remain distinguishable when their thickness is greater than the subgrain diameter; however, the serrations have been developed in the very elongated grains and the original grain boundaries are lead to pinching off as the grain average thickness falls below the subgrain size. Kassner [17] et al reviewed the GDRX phenomenon in the large-strain deformation of aluminum alloys by aspects of low/high angle boundaries and suggested that testing of aluminum single crystal would be useful to verify GDRX concept by absence of high angle grain boundaries. However, when Gourdet and Montheillet [8] investigated the microstructure of single and polycrystalline aluminum in hot uniaxial compression and torsion, the formation of grain boundaries was identified as a type of continuous dynamic recrystallization mechanism (CDRX). Their observations indicated that subgrain boundaries with progressive accumulation of dislocations could effectively evolve into grain boundaries at the critical misorientation angle of 15°. CDRX has further been investigated in various aluminum alloys subject to severe plastic deformation by Sakai and co-workers [18–20]. The strain-induced high angle boundaries for this

* Corresponding author at: State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China.
E-mail address: tangding@sjtu.edu.cn (D. Tang).

http://dx.doi.org/10.1016/j.matchar.2016.06.025
1044-5803/

mechanism in hot torsion were modeled by Barnett and Montheillet [9]. The importance of CDRX seems to be great at lower equivalent strains [8] while GDRX is favored at high equivalent strains [13]. In this study, the microstructure and its evolution are firstly characterized during the porthole die extrusion, especially in the welding chamber. According to these two dynamic recrystallization mechanisms, an assessment of the grain structure evolution is reported. And it is critical for modeling and predictions of the dynamic recrystallization grain morphology.

The webs of the MPE tube are formed in the solid state bonding process. The soundness of bonding represents the welding quality. Criteria for welding quality predictions are of particular interest with the aim to optimize the die geometry design and extrusion parameters [21–23]. FEM methods provide an accurate evaluation of the fields of contact pressure, flow stress and velocity on the welding surface to make better predictions associated with the improved criteria [24,25]. However, the problems arise with the verification of these criteria because welding strength depends not only on the mechanics of the process, but also on its metallurgy, starting from billet casting, homogenization, up to the heat treatment after extrusion. The elongation and the ultimate strength significantly depend on grain size and anisotropy, oxides and inclusion and so on [5,26,27]. Although Edwards [28] and Tang [2] physically simulated welding process to verify FEM prediction, such simulation has its inherent limitations. It is hardly to obtain the oxide-free surface for welding. The direct and overall microstructural investigation on the porthole die extrusion is still lacking. Furthermore, Yasuda's research on the elongation of seam welded aluminum alloy indicates that texture gradient from weld to non-weld region would accelerate the failure of the tensile specimen [5]. Bingöl's experimental results also found striking differences in strength and elongation between tensile specimens at seam weld regions parallel and perpendicular to extrusion directions [27]. It is true that Güzel [14] et al have taken the preliminary exploration of the grain structure evolution along the material flow line by means of designing a specific bar extrusion setup. The grain structure evolution and the development of texture variation through the thickness of seam welds remain unclear so far. Therefore, a thorough understanding of the microstructure, especially the texture gradient, considering its effect on welding quality in the porthole die extrusion is a research of great interest.

In this study, an assessment of microstructure evolution in the porthole die extrusion of aluminum alloys AA 1100 is provided to investigate the aluminum thermal-mechanical restoration mechanism and the development of grain anisotropy. Respective materials points on the three material flow lines are chosen to capture the features of grain development and texture variety in the whole process. Microstructure characterization is aided by optical microscopy and electron backscattered diffraction (EBSD) techniques. The statistics of grain size and grain aspect ratio is conducted according to EBSD mappings. The texture evolution along the forming path and texture gradient through the thickness of the tube web are discussed in detail in the following sections.

2. Experimental procedures

2.1. Materials

The material used in this study was an AA1100 commercial-purity aluminum alloy. The chemical composition of the alloy is given in Table 1.

2.2. Multi-port extrusion procedure

The micro multi-port extrusion tube is produced by Conform^{TM} extrusion, which is a continuous extrusion process. An aluminum rod is frictionally fed into a channel continuously from a wheel which would then be rotated. An abutment stops the movement of the material, and the continuous feed causes it to fill the channel and then engage the stationary surface of the shoe confronting the channel. Meanwhile, the material, heated by friction of the process, begins to yield and is forced into the porthole extrusion dies. Fig. 1a shows the extrusion shoe where the porthole dies was set. The porthole extrusion dies, used to form the micro multi-port extrusion, are shown in Fig. 1b. When the materials are pushed into the die, it is divided into two sections by the porthole bridge. Then, the two sections of metal flow through the two portholes into the welding chamber. They are welded as they go through the mandrel teeth. Once the welding chamber is filled, the metal is pushed out of the die bearing, and the profile of the tube is formed.

2.3. Metallography

Microstructure is characterized by optical microscopy (OM) and electron backscattered diffraction (EBSD) analysis on the section as illustrated in Fig. 2. Samples for OM are ground and polished using alumina suspension and 0.02 μm colloidal silica suspension, then etched with modified Keller's etchant. For EBSD mapping, they are ground and polished to 2000# SiC paper, and then electropolished by LectroPol 5 with electrolyte A2. EBSD examination is carried out by NOVA NanoSEM 230 with AZtec HKL Max System. A high angle boundary is defined by OIM analysis software as the boundary with misorientation angle of $\theta \geq 15°$, a low angle boundary such as that of $2° \leq \theta < 15°$. The misorientation of $\theta < 2°$ is excluded. The ODF sections are calculated by the series expansion method using HKL Salsa software. The resolution is $32 \times 16 \times 16$. The Gaussian half width is 5. L_{max} is equal to 22. Data clustering is on with the value of 5.

3. Results

3.1. Material flow lines

Fig. 3 shows the grain structure of the extrusion butt using OM. It is observed that grain structure close to the mandrel and the die cap are quite different from that in the middle of the porthole section. The former tends to be elongated during the whole extrusion process, while the latter is nearly equiaxed in the shear intensive zone. Therefore, three flow lines, marked A, B and C, are sketched as shown in Fig. 4. The flow line A is 1.8 mm close to inner surface of the die cap, and the flow line C is 1mm away from the mandrel surface. The forming paths along flow line A and C are strongly influenced by their contact with die surface.

By analyzing the development of grains, six different zones are observed in the extrusion residue, analogous to the experiments conducted by Güzel [14]. Along the extrusion direction (ED), the first zone is inlet zone (IZ) where most of grains are equi-axed since they are deformed after a process like equal channel angular extrusion. The following zone is defined as transition zone (TZ). Material in this area undergoes some shear deformation because of friction of the billet/die. The material in the middle moves faster than that on both sides. The

Table 1
Chemical composition of AA1100.

AA1100	Si	Fe	Mn	Mg	Cu	Ti	Zn	Cr	Zr	Ni	Al
wt.%	0.09	0.23	0.0005	0.01	0.18	0.02	0.0035	0.0015	0.0025	0.01	99.39