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# Microstructure and mechanical properties development of micro channel tubes in extrusion, rolling and brazing

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ABSTRACT

In addition to extrusion, the post-processing of rolling and brazing has significant effect on the mechanical properties of multi-port tubes. The aluminum micro channel tubes, especially the seam welding zone in the internal webs, are investigated in terms of mechanical tests, microstructure characterization, and finite element analysis. The effect of the post-process of rolling are quantified by varying amount of rolling reduction ratios. Tensile strength and pressure bearing capacity are determined by tensile tests and burst pressure tests, respectively. The evolution of the microstructure within the seam wielding zone is characterized by Electron backscattered diffraction (EBSD) and optical microscopy (OM). The fracture profile observed by OM indicates ductile fracture mode. The pressure bearing capacity is reduced by ~47% at 5% reduction ratio of rolling followed by 3-minute brazing, where largest grains are obtained due to abnormal grain growth.

## 1. Introduction

Multi-port extrusion (MPE) tubes are important and necessary parts to convey the substances which can flow under pressure, such as liquid, gas, slurries, etc. The design of the MPE tubes is not only to satisfy the requirement of transporting the substances, but also to withstand internal pressure with minimization of materials and manufacturing costs. As structural members, internal walls are seam welded under sufficiently high pressure within a welding chamber of a high precision porthole die [1]. Failure of an MPE tube commonly initiates at the internal walls under burst pressure experiments [2, 3]. The mechanical property of the tubes is determined by the internal walls, whose mechanical property is associated closely with the microstructure, such as grain morphology, grain size, texture, etc. [4–6]. Therefore, investigation of the microstructure and its evolution of internal walls during manufacturing processes is of great industrial significance.

The microstructures of aluminum alloys under thermomechanical deformation and have been extensively investigated [7–11]. Dynamic recovery is likely to occur due to the high stacking fault energy of aluminum alloys. Highly polygonised sub-grains are formed due to the movement and annihilation of dislocations at elevated temperature. Geometric dynamic recrystallization (GDRX) mechanism has been proposed by McQueen and coworkers to interpret the phenomenon of serrated grain boundaries [12–17], which is first observed in Al-5Mg and Al-Mg2Si alloys [12] and commercial aluminum alloy [16]. Though elongating with increasing deformation, the original grains remain distinguishable when their thickness is greater than the sub-grain size. However, the serrations have been developed in very elongated grains with thickness smaller than the sub-grain size and eventually lead to pinching off of the grains. In addition, the mechanism of continuous dynamic recrystallization (CDRX) was identified to form the grain boundaries during the investigation of the microstructure of single and polycrystal aluminum in hot compression and torsion. Sub-grain boundaries with progressive accumulation of dislocations could effectively evolve into grain boundaries at the critical misorientation angle of 15°. The mechanism of CDRX has been investigated in various aluminum alloys subject to severe plastic deformation [18–20]. The importance of CDRX seems to be great at lower equivalent strains [8], while GDRX is favored at high equivalent strains [13]. These two dynamic recrystallization mechanisms are also important for the development of the microstructure in the internal walls. In addition, abnormal grain growth is also responsible for the significant change of microstructure aluminum alloys [7].

The internal walls of the MPE tube are formed in the solid-state bonding process during extrusion. The extrusion welding has been investigated in terms of mechanical experiments and simulations [21–24]. Corresponding criteria associated with the contact pressure, the flow stress and velocity on the welding interface have been

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**Table 1**
Chemical composition of the aluminum alloy (AA1100).

| Si | Fe | Cu | Mn | Zn | Al | Others |
|---|---|---|---|---|---|---|
| 0.09 | 0.23 | 0.18 | 0.0005 | 0.0035 | 99.39 | 0.106 |

proposed to guarantee the welding quality of the MPE tubes. Moreover, the microstructure evolution during extrusion and its effect on the welding quality has been carefully studied to assess these criteria [25]. However, the welding quality is not only affected by extrusion, but also by the subsequent processing required for final products. In real manufacturing, the post-process of cold working (e.g., rolling, bending, expanding, etc.) is required to satisfy the dimensional accuracy, while brazing is required to assemble the MPE tubes. Poorganji et al. [26] have found that cold working affected the microstructure and the property of AA6451 alloy plate significantly. As a consequence, the effect of the post processing on the development of the mechanical behaviors of aluminum alloy MPE tubes is expected to be significant and is a research of great interest.

In this study, the effect of the processing chain of extrusion-rolling-brazing (E-R-B) on the mechanical properties of the produced MPE AA1100 aluminum alloy tubes is investigated. Seam welding interface is formed in the internal walls during extrusion. The microstructure and the properties of the internal walls are further changed by the subsequent rolling and brazing processes. Uniaxial tension and burst pressure tests are conducted to study the mechanical behaviors of the MPE tubes. Corresponding microstructures are characterized with the aid of electron backscattered diffraction (EBSD) techniques, optical microscopy (OM) and finite element method (FEM). The equivalent strengths of the MPE tubes, associated failure modes, and evolution of microstructure around seam welding zone are discussed in detail.

## 2. Experimental Procedures

### 2.1. Materials

The material used in current study is AA1100 aluminum alloy, which is widely used in heat transfer products such as automotive radiators and air conditioners. The chemical composition of the alloy is listed in Table 1. The AA1100 alloy is easy to be extruded and brazed because of its excellent workability, weldability, and corrosion resistance.

### 2.2. E-R-B Processing Chain

The experimental specimens are prepared in terms of the processing chain consisted of extrusion-rolling-brazing (E-R-B). The micro channel tubes are produced by the porthole extrusion dies with the specially designed mandrel teeth (Fig. 1a). An aluminum alloy billet is fed into the die, divided into two sections by the porthole bridge, and welded in the welding chamber. The parameters associated with the extrusion are listed in Table 2. Tubes with ten micro channels are produced with the cross section shown in Fig. 1b. The width and height of the tube section are 16 mm and 2 mm, respectively. The thickness of the micro wall is 0.3 mm and the size of the hole is 1.2 × 1.2 $mm^2$. Between the upper and lower sections, seam welding planes (seam welding lines in the cross section) are formed in the micro walls (Fig. 1b).

Due to the gradual wearing of the extrusion die, the dimensional requirement of the tubes is not able to be satisfied. Additional process of rolling is required necessarily to standardize the tubes with appropriate reduction ratios (Fig. 1c). As a consequence, different strains are applied to the tubes as well as to the internal walls. To understand the effect of the rolling process, the extruded micro-channel tubes are rolled with different amount of reduction ratios. The samples are denoted as E-Red (x%) tubes, where x% is the amount of the reduction ratio, which

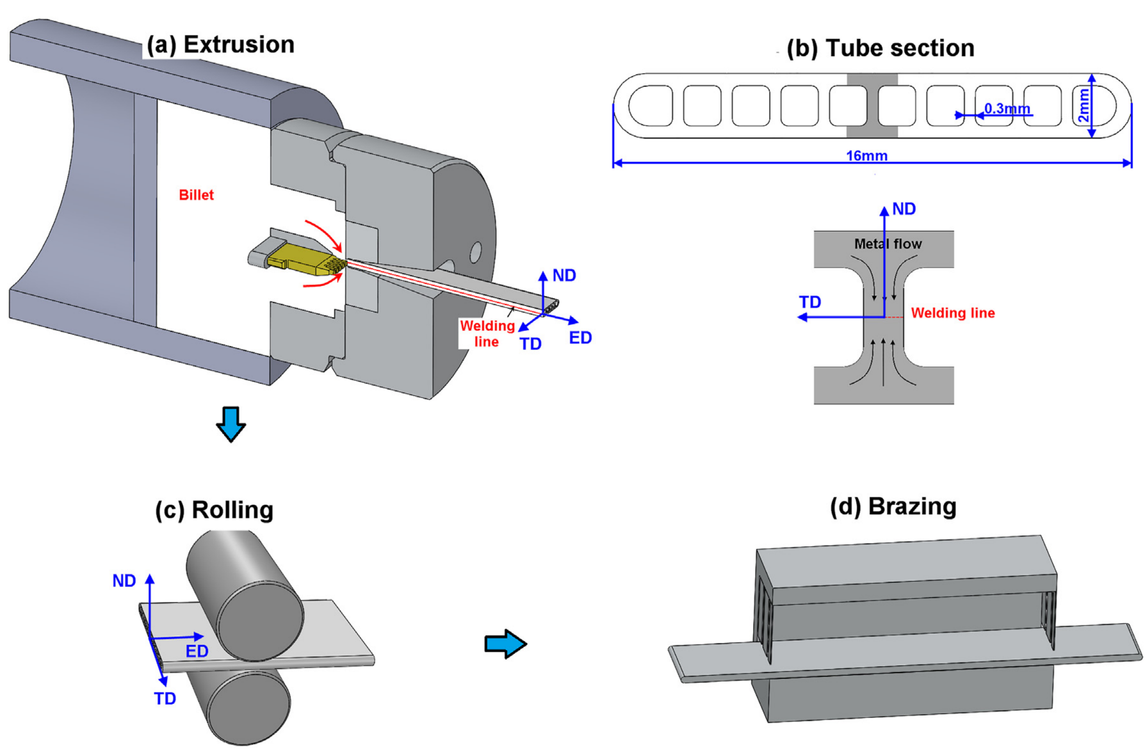


**Fig. 1.** Schematic of the processing chain of extrusion-rolling-brazing (E-R-B) for micro-channel tubes: (a) Extrusion, (b) cross section of the tube and formed welding line, (c) rolling, and (d) brazing.