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Effect of die design in microchannel tube extrusion

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Abstract

Microchannel tube (also called Multi-port extrusion tube) with sub-millimeter-diameter ports in the cross-section is a newly developed type of aluminum extrusion with the basis for its design in micro-scale heat transfer theory. Comparing to traditional heat exchanger tube with channel diameter more than 2 mm, microchannel tube has great advantage on high heat transfer efficient, light weight, high pressure bearing capacity. The main difficulty on the tube fabrication is the extrusion porthole die design. In this work, design of the extrusion die of the microchannel tube is studied with both numerical method and experiments. Seam welding strength and microstructures of the tube formed with different designs of die are investigated. Forming experiment and hydrostatic pressure tests to the tubes formed is done for validation. And microstructure of the tube is observed using electron backscatter diffraction (EBSD) method.

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Keywords: Microchannel tube; Extrusion; Seam welding;

1. Introduction

Microchannel tube (also known as micro-multiport tube) is a kind of heat exchange tube with a row of side-by-side channels whose diameters are less than 1 mm. Fig. 1 shows microchannel tubes with different section shape. During the last decade there has been growing interest in the new type heat transferring tubes for its energy saving character. The special injection flow mode inside the microchannels greatly increases the heat exchanging efficiency. Beside, microchannel tube has advantages of light weight and high pressure bearing capacity, which

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finds more and more applications in automotive condenser, gas cooler and commercial/house hold air conditioning. The diameter of the tube trends to be smaller with the requirement of energy efficient.

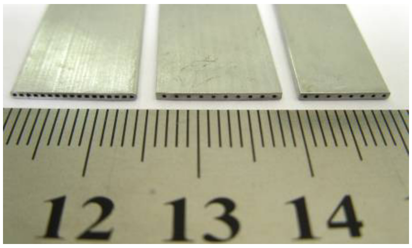

Fig. 1. Microchannel tubes.

Microchannel tube is formed with porthole extrusion die. The diameters of the mandrels forming the microchannels are also very tiny. The mandrels are of cantilever structure and easy to deform or break during the extrusion process. Therefore, to maximize the mandrel lifetime, the length of the cantilever should be as short as possible. However, short mandrel will cause poor seam welding condition of the extrusion process which eventually affected the pressure bearing capacity of the tube. A balance between weld quality and mandrel performance should be found in extrusion die design.

Many criteria have been proposed for seam weld quality evaluation. Donati et al. (2004) improved the evaluation methodology by taking multiple factors of the welding chamber into consideration and proposing a criterion based taking pressure, time, and material flow into account. Bozzi (2009) used a novel Lagrangian approach to integrate variables along the actual welding paths to get a deeper insight into the seam weld quality along the tube thickness. Liu (2010) has evaluated effects of process parameters and die geometry on welds quality, but such results are not validated with experiments. Hiramoto (2009) has studied the stress distribution on the extrusion die of the microchannel tube.

In this work, seam welding strength and microstructures of the tube formed with different designs of die are investigated. Forming experiment and hydrostatic pressure tests to the tubes formed is done for validation. And microstructures of the tube is observed using EBSD method.

2. FE simulation of the extrusion process

In this study, two designs of the extrusion dies with flat and hemispherical pressure bearing surface are examined, shown in Fig. 2. FE simulation was performed using the software package DEFORM 3D. The FE simulation of the billet and the porthole die is carried out with quarter symmetry boundary conditions. The material of the billet is AA 3003 aluminum alloy with basic material properties shown in Table 1. The extrusion tool is composed of die, container and stem. Heat exchange between the workpiece and tooling was incorporated in the FE calculation, while heat transfer between tooling/extrudate and the ambient surrounding was ignored.

The shear-type friction conditions at the workpiece and tooling interfaces were imposed as part of the boundary conditions. As the thickness of the tube wall is only 0.25 mm, the initial mesh size of the billet is set to be 0.5mm which is smaller than most of studies on the aluminum extrusion. And self-adapting remeshing was applied which is able to solved the problems of local intensive deformation, for example, near the die bearing.

From the FE simulation results, the die filling process during the extrusion can be seen in Fig.3. The billet is first divided into two sections through the two portholes in the die. Then, as the metal flows into the welding chamber, the two sections are rejoined through the mandrel teeth. After the welding chamber is filled, the metal is pushed out of the die bearing, and the profile of the tube is formed.

Table 1. Processing parameters of extrusion process.

	Parameters	Values
Billet material property	yield stress, σ_s (MPa)	45
	Ultimate tensile strength, σ_b (MPa)	115
Processing parameters	Ram speed (mm/s)	5
	Die temperature (ºC)	450
	Friction coefficient (billet–container)	0.7
	Friction coefficient (workpiece–die)	0.4

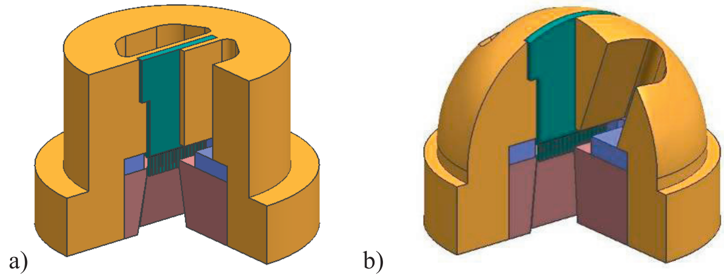

Fig. 2. Extrusion dies for microchannel tube. (a) Flat extrusion die and (b) hemispherical die.

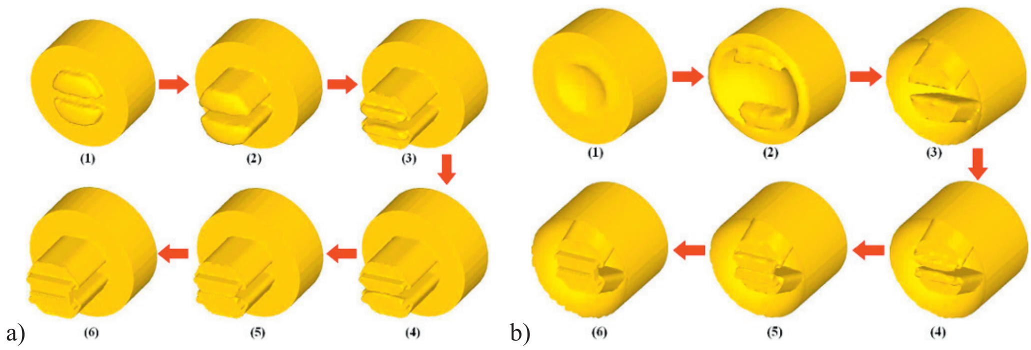

Fig. 3. Die filling process during the tube extrusion. (a) Flat die and (b) hemispherical die.

3. Seam welding strength

From the simulation results, filed variables on welding surface from numerical simulation results can be obtained. The effective stresses on the welding surface for extrusion through flat and hemispherical die are 47.6-58.2 MPa and 45.9-57.4 MPa, respectively. For the two designs of die, the variation pattern of effective stress along extrusion direction is similar.

Fig. 4 shows effective stress variation on welding surface along extrusion direction for the spherical die. Obviously, each welding surface can be divided into four regions which is flow dead zone, main welding zone, die bearing zone and die bearing exit zone. As is in Fig. 4, the first region along the extrusion direction is flow dead zone, in which metal flows slowly and effective stress is relatively small. In the main welding zone, effective stress increases to a high value at the beginning and then decreases. Subsequently, metal flows into the third region, die bearing zone, characterized by a rapidly increasing effective stress until its maximum. In this region, the metal is accumulated and compressed continually in order to flow out from the small-diameter die bearing. After extruded from the die bearing, the metal is released and effective stress decreases rapidly in the last region, die bearing exit zone.

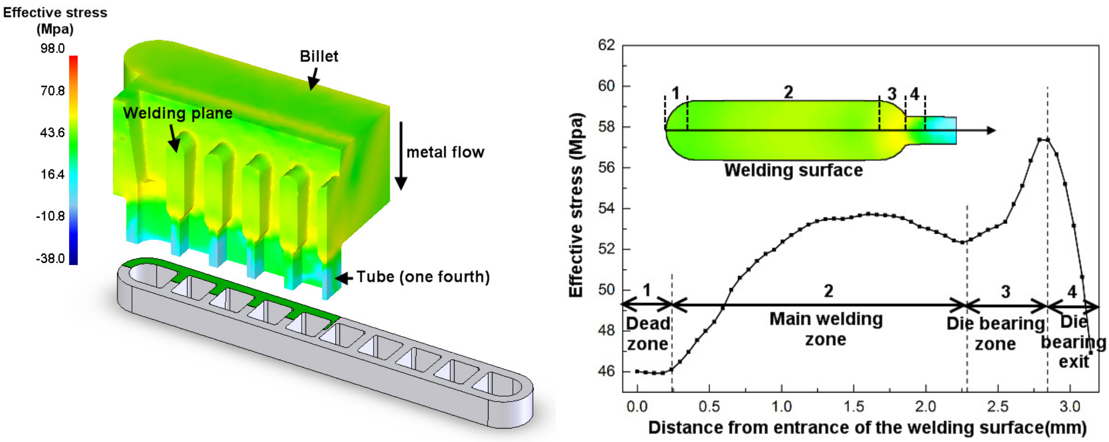

Fig. 4. Distribution of effective stress on welding surface.

With the distribution of effective stress on welding surface, seam welding condition can be examined. In this study, K-parameter method proposed by Donati et al. (2004) is applied to examine the seam welding property.

$$K = \int_L \frac{p}{\sigma} \mathrm{d}L = \int_t \frac{p}{\sigma} \cdot v \cdot \mathrm{d}t \quad (1)$$

where L is general path from entrance of the welding surface to exit of die bearing and v represents metal flow velocity of any point on the welding surface. The K-parameter method takes not only the effect of welding pressure but also the role of metal flow velocity and welding time on welding quality into considered. As a result, as a welding quality index, K-parameter method can describe welding behavior well and predict welding quality effectively.

Based on finite element method, parameter K can be written as a discrete form as follow.

$$K = \sum_{i=1}^{l} \sum_{j=1}^{m} \frac{p_{ij}}{\sigma_{ij} v_{ij}} v_{ij} = \sum_{i=1}^{l} \sum_{j=1}^{m} \frac{p_{ij}}{\sigma_{ij}} \quad (2)$$

where l and m are the number of elements on the welding surface along the height and width direction, which define the whole welding surface. v_{ij} represents node speed, inversely proportional to residence time at any point and the welding surface includes all possible welding paths. Considering the average effect of all welding paths on the welding surface, welding quality factor Kad can be written as a parameter related to width of the welding surface.

$$K_{\mathrm{ad}} = \frac{1}{m} \sum_{i=1}^{l} \sum_{j=1}^{m} \frac{p_{ij}}{\sigma_{ij}} \quad (3)$$

Welding quality factor K is a non-dimension parameter and the higher its value is, the better welding quality will be. Under the temperature in welding chamber remaining same, field variables affecting welding quality index K include welding pressure, effective stress and metal flow velocity, among which welding pressure can be replaced by hydrostatic pressure on the welding surface approximately. Through extracting above field variables from numerical simulation results and plugging these data into Eq. (3), we can obtain welding quality index K which is used to evaluate welding quality.

According to calculating results, the welding quality index for extrusion through flat and Hemispherical die are 154.7 and 196, respectively. Obviously, the former is less than the latter and that shows welding quality of microchannel flat tube extruded through Hemispherical die is better than that of flat die under the same process conditions.

4. Extrusion experiment

Forming experiments with the same design of the die as the FE simulation and also the settings of the temperature and welding chamber height is carried out. Hemispherical extruiosn die and tube extruded with this die is shown in Fig. 6. A hydrostatic pressure test is done to examine the tube's welding strength. The average failure pressure of the tube formed with hemispherical die and flat die is 28 and 22 MPa, respectively. This result agrees with the seam welding strength analysis.

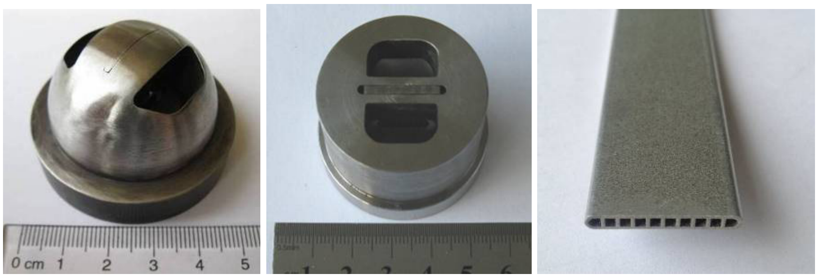

Fig. 5. Hemispherical die, flat die and tube extruded.

5. Microstructure observation

Microstructure of the tube formed with hemispherical die is investigated using EBSD, which allows determining and quantifying the grain sizes and subgrain misorientations. Equiaxed grains are present in the grain boundary mapping of the tube on the cross-section as shown in Fig. 6. Grains located in the junction between two tube walls are smaller than those in the central position of tube walls. Although there are 6 grains with the large diameter in certain locations of tube walls, subgrain boundaries, by which these grains were separated into several approximately equal parts, are clearly observed in these grains. The subgrain size is close to grains nearby. The yield strength increases as the subgrain size decreases. Refined subgrains are helpful to strengthen the material. Therefore, these large grains with subgrain boundaries included would not destroy overall performance of the microchannel tube.

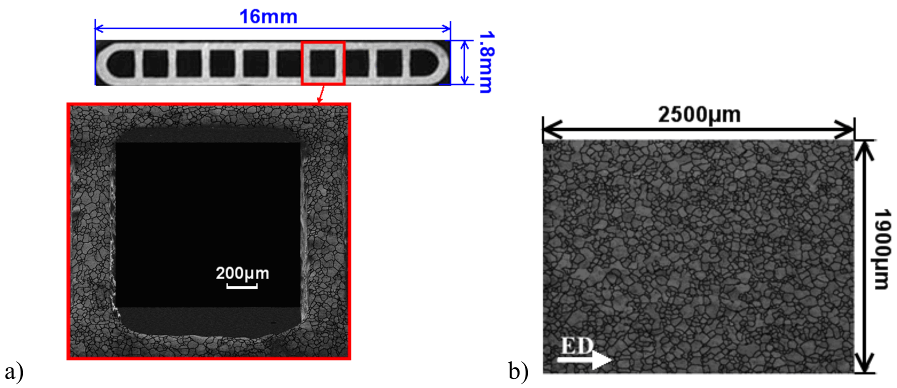

Fig. 6. Grain boundary mapping. (a) Cross-section and (b) longitudinal-section.

Fig. 6(b) shows the grain boundary mapping on longitudinal section. Large equiaxed grains are mixed with small equiaxed grains, which have chainlike distribution. And no extrusion band has been observed along the deformation direction. It is indicated that the microstructure of the tube after hot extrusion is fully recrystallized with no deformed grains.

6. Conclusions

In this work, design of the extrusion die of the microchannel tube is studied with both numerical method and experiments. Seam strength and microstructures of the tube formed with different designs of die are investigated. A hydrostatic pressure test is done to examine the tube's welding strength. Microstructures of the tube is observed using EBSD method.

Based on this investigation, the following conclusions can be drawn:

(1) Numerical results with K-parameter method shows that welding quality of tubes formed with hemispherical die is higher than that of flat die. And it agrees with hydrostatic pressure test to the tubes formed with the two types of extrusion dies.

(2) Equiaxed grains are present in the grain boundary mapping of the tube on the cross-section. For the longitudinal section, large equiaxed grains are mixed with small equiaxed grains, which have chainlike distribution.

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