CIRP Annals - Manufacturing Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Large reduction die-less mandrel drawing of magnesium alloy micro-tubes

Tsuyoshi Furushima [a,*], Ken-ichi Manabe [b]

[a] Institute of Industrial Science, The University of Tokyo, Tokyo, Japan
[b] Department of Mechanical Engineering, Tokyo Metropolitan University, Tokyo, Japan

Submitted by Manabu Kiuchi (1), Tokyo, Japan

ARTICLE INFO

Keywords:
Forming
Magnesium
Die-less drawing

ABSTRACT

Die-less drawing using wire mandrel was proposed aiming to develop the process to manufacture magnesium (Mg) alloy micro-tubes. The ratio of thickness to outer diameter of drawn tubes was controlled by changing drawing speed and feeding speed referring to the formula derived from “volume constancy principle”. The results were as follows. The attainable reduction limit was enhanced by raising heating temperature of mother tubes and the maximum cross-sectional reduction of 58.3% was obtained through a single pass drawing. Mg alloy micro-tubes with outer diameter of 3.35 mm and wall-thickness of 0.69 mm were fabricated through the optimized multi-pass drawing. Mg alloy micro-tubes developed in this study can be used for medical, medicinal, sanitary and chemical appliances.

1. Introduction

Magnesium (Mg) alloys are excellent materials for wide application owing to their specific strength, rigidity and lightness. In these decades, the weight reduction of the transportation machines, such as automobile, by using Mg alloys has attracted keen attention of researchers and engineers. Recently, various type of Mg alloys have been developed and research works aiming actual application started widely. One of these new alloys has a peculiar characteristic desirable for metallic implants due to its miracle bio-absorbability, as well as, good bio-compatibility, non-toxicity and mechanical strength [1]. Furthermore, various new Mg alloys are emerging having excellent abilities such as high strength with long period stacking order structure (LPSO), flame resistance and high corrosion resistance [2]. In the situation like this, tubular products of Mg alloys including micro-tubes are becoming more and more important core materials for medical tools and parts, for example, injection needle, bone-joint implants and blood-tube stents.

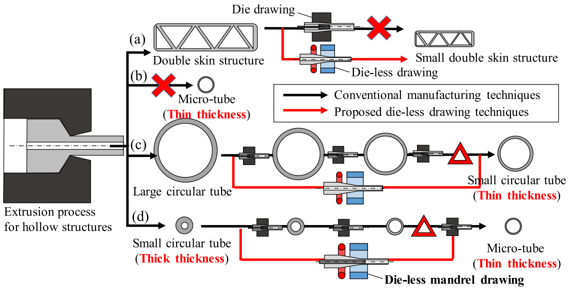

Fig. 1. Mass manufacturing process for Mg alloy tubular products.

In general, it is possible to manufacture Mg alloy tubular products such as not only circular tube but also non-circular tubes like double skin structure through extrusion as shown in Fig. 1(a) . However, to make tubes with micro-diameter and thin-wall is difficult (Fig. 1(b)) due to size effects related to grain size, friction and dies and tools manufacturing [3]. Die drawing can be used for making micro-tubes, but it is not able to accomplish large reduction in cross section and wall thickness through single pass, because of low deformability of Mg alloys (Fig. 1(c) and (d)). Usually, the maximum attainable reduction in cross section is about 5% through cold drawing [4], 15% by warm drawing [5]. Consequently, many drawing passes and intermediate annealing are required for manufacturing Mg alloy micro-tubes.

In the previous studies, Tiernan et al. and the present authors discussed the die-less drawing without using any supporting tools for rods [6] and tubes [7]. In the study, the die-less drawing was applied to AZ31 Mg alloy and the reduction in area of 60% was obtained [8]. However, it was difficult to perform the active thinning of wall thickness because the ratio of thickness to outer diameter is usually unchanged through die-less drawing [9] for manufacturing Mg alloy micro-tubes with thin thickness.

In this paper, the novel die-less mandrel drawing will be discussed. The long wire mandrel is inserted into the mother tube and subjected to die-less drawing. The expected challenges of the proposed die-less mandrel drawing are whether a large reduction in area can be accomplished in spite of contacting with the inner wall of the tube due to the mandrel. In addition, it is also necessary to discuss whether wall thinning and controllability of the cross-sectional shape. For these challenges, the fundamental deformation features,

---

[*] Corresponding author.
E-mail address: tsuyoful@iis.u-tokyo.ac.jp (T. Furushima).

https://doi.org/10.1016/j.cirp.2018.04.101
0007-8506/© 2018 Published by Elsevier Ltd on behalf of CIRP.

Please cite this article in press as: Furushima T, Manabe K-. Large reduction die-less mandrel drawing of magnesium alloy micro-tubes. CIRP Annals - Manufacturing Technology (2018), https://doi.org/10.1016/j.cirp.2018.04.101

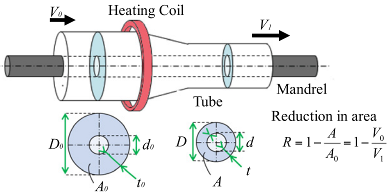

Fig. 2. Schematic illustration of die-less mandrel drawing.

such as change in cross-sectional shape and dimension, drawing limit (maximum reduction) and surface roughness of drawn tubes were investigated. Through the study, a new die-less mandrel drawing for mass-manufacturing of Mg alloy micro and thin tubes is proposed. The concept of new die-less mandrel drawing techniques is drawn with a red line in Fig. 1.

2. Die-less mandrel drawing

Fig. 2 shows the schematic illustration of the die-less mandrel drawing, that is the die-less drawing using mandrel, developed in this study. A long wire mandrel is inserted into a mother tube from top to end and the tube is subjected to die-less drawing. To the tube, feeding speed V_0 is given on inletting stage and pulling/drawing speed V_1 is given on outcoming stage. The tube is heated locally using an induction coil. Through drawing, the outer diameter of tube reduces at heated zone, and inner diameter is kept unchanged by the mandrel. Thus, the wall thinning occurs during drawing. To predict the cross-sectional shape and dimension of drawn tube, the following equation based on volume constancy law can be used.

$$A_0 V_0 = A V_1 \tag{1}$$

The reduction in cross-sectional area obtained through a single pass is derived from the speed ratio V_0/V_1.

$$R = 1 - \frac{A}{A_0} = 1 - \frac{V_0}{V_1} \tag{2}$$

The inner diameter d_0 does not change through drawing due to restriction given by the mandrel. Substituting the cross sectional area A_0 and A_1 into Eq. (2), the outer diameter D after drawing is expressed as follows,

$$D = \sqrt{{d_0}^2 + \left({D_0}^2 - {d_0}^2\right)\frac{V_0}{V_1}}. \tag{3}$$

The wall thickness t of drawn tube depends on speed ratio V_0/V_1 as expressed by next equation.

$$t = \frac{1}{2}(D - d) = \frac{1}{2}\left\{\sqrt{{d_0}^2 + \left({D_0}^2 - {d_0}^2\right)\frac{V_0}{V_1}} - d_0\right\} \tag{4}$$

By combining conventional die-less drawing [9] and proposed die-less mandrel drawing, the desired cross-sectional shape would be controlled flexibly based on above equations.

3. Materials and experiments

In case of extrusion of tubes with small diameter, it is very difficult to obtain thin wall thickness due to size effects [3]. In this study, mother tubes are extruded AZ31 Mg alloy tubes which have outer diameter of D_0 = 5 mm, inner diameter of d_0 = 2 mm, and wall thickness of t_0 = 1.5 mm. A steel wire SWP-A with diameter of 2 mm was used as the mandrel. Graphite was used as a lubricant between contacting surfaces of tube and mandrel.

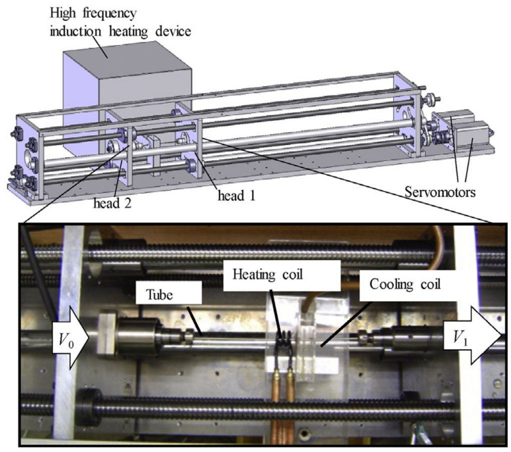

Fig. 3. Schematic illustration and photograph of die-less mandrel drawing apparatus.

Fig. 3 shows the schematic illustration and photograph of the die-less mandrel drawing apparatus used in this study. This apparatus has the drawing and feeding heads with chucks for gripping tubes. Both heads were driven by two servo motors with power of 750 W respectively through ball screws with lead of 5 mm. Each servomotor for V_0 and V_1 was controlled independently by homemade program in PC. Collet chucks on the motion heads were adjusted to grip tested tubes. A high frequency induction heating apparatus having a power of 2 kW/2.2 MHz was used for high-speed zone heating. Water at room temperature cooling system and atmospheric cooling (denoted as "no cooling") were used with aim to investigate the effect of cooling. The heating temperature was measured by a radiation thermometer. The heating temperature from 250 ~ 450 °C was adjusted by controlling input power to the induction heating coil. Through the experiments, the fixed feeding speed V_0 of 0.5 mm/s was employed. The drawing speed V_1 was changed for controlling the reduction in area based on Eq. (2). After the drawing, the mandrel was pulled out from the tube without difficulty by the difference in shrink deformation due to thermal expansion coefficients of tube (magnesium: 26.0×10^{-6}/K) and mandrel (steel: 12.3×10^{-6}/K). Concerning the quality of drawn tubes, the surface roughness was measured by a confocal laser microscope.

4. Results and discussion

4.1. Cross-sectional shape/dimension obtained through die-less mandrel drawing

Fig. 4 shows the effect of drawing speed V_1 on axial and cross-sectional shape and dimension of drawn tubes, here, V_0 = 0.5 mm/s, heated zone temperature = 400 °C and no cooling. The outer diameter of drawn tube decreases with increase in the drawing speed V_1. When V_1 is too fast, such as 1.0 mm/s in this case, unstable deformation and fluctuation of diameter occurs at early stage of drawing. Here, the necking at the early drawing stage is called as unstable deformation. Fig. 5 shows the effect of speed ratio V_1/V_0 on the outer diameter D, inner diameter d and thickness t under various heating temperature and no cooling. The plots were obtained through the experiments and the curves were obtained by using Eqs. (3) and (4). From the results, it is clear that the inner

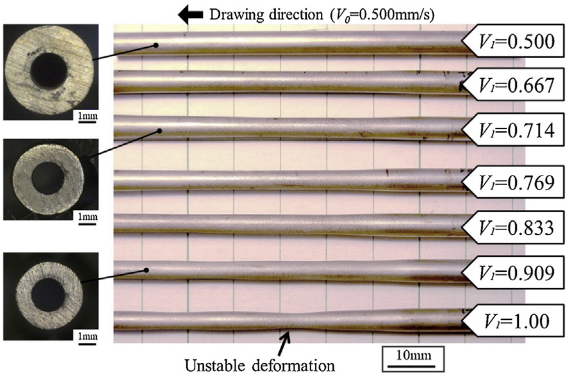

Fig. 4. Effect of drawing speed V_1 on axial and cross sectional deformation of tubes.

Please cite this article in press as: Furushima T, Manabe K-. Large reduction die-less mandrel drawing of magnesium alloy micro-tubes. CIRP Annals - Manufacturing Technology (2018), https://doi.org/10.1016/j.cirp.2018.04.101