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A novel superplastic dieless drawing process of ceramic tubes

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ABSTRACT

A novel superplastic dieless drawing was performed for fabrication of ceramic tubes. The reduction in area of tube obtained through the drawing was controlled by changing feeding and drawing speeds. Some tested tubes showed extremely low drawing stress of 15 MPa and high value of strain rate sensitivity parameter of 0.42. Furthermore, the maximum reduction in area of 84% was accomplished through single pass drawing. Thus, the ceramic tubes showed a good superplasticity in the proposed process. The conclusion is that the proposed superplastic dieless drawing can be widely used for efficient fabrication of various ceramic tubes.

1. Introduction

Recently, a compact solid-oxide fuel cell (SOFC) was proposed for down-sizing and higher efficiency of the fuel cell with aim to innovate car driving system [1]. The compact SOFC consists of micro ceramic tubes expecting high performance (see Fig. 1) [2]. These tubes are required to accomplish further miniaturization. Mother ceramic tubes are manufactured through sintering after sharping processes such as powder paste extrusion, powder injection molding or press forming of powder to half tubes and bonding them to round tube. However, their size is not so small, therefore, an appropriate mass production process to reduce their size and make into micro ceramic tubes are required to extend the proposed SOFC.

Normally, the ceramics are not subjected to plastic forming due to hard and brittle characteristics. Meanwhile, the ceramics show superplastic deformation at the high temperature range from

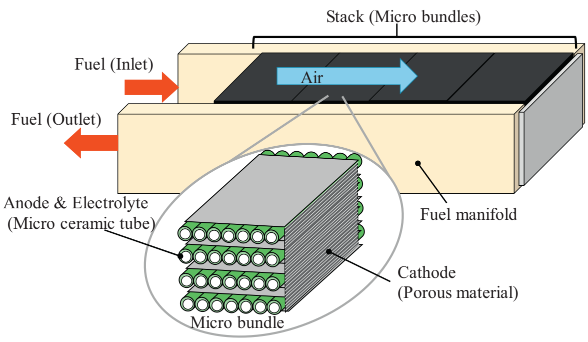

Fig. 1. Schematic illustration of compact SOFC consisting of micro ceramics tubes.

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1400 to 1700 °C, reported by Wakai et al. [3]. However, dies and tools cannot be practically safe in such high temperature. Therefore, the ceramics cannot be delivered, in general, to the practical plastic forming processes.

On the other hand, Weiss and Kot proposed the dieless drawing by introducing local heating of metal bars [4]. The authors proposed a superplastic dieless drawing for fabrication of microtubes and the effectiveness of the process was demonstrated for manufacturing superplastic metal tubes [5–7].

In this study, the authors intend to propose a novel superplastic dieless drawing for effective and expectable mass manufacturing of micro ceramic tubes SOFC used in fuel cell car. For this final goal, a superplastic dieless drawing apparatus with acetylene burner for obtaining ultra-high temperature over 1700 °C has already designed for 3Y-TZP tubes in our previous study [8]. The performance of designed apparatus such as load and temperature distribution measurements in the dieless drawing were evaluated. However, detailed deformation behaviour of zirconia ceramic tubes in the superplastic dieless drawing has not been clarified adequately.

In this paper, the fundamental deformation behaviour of zirconia ceramic tubes were investigated in the superplastic dieless drawing by using designed apparatus. Geometry of cross-section and surface roughness of drawn tubes and necessary drawing stress were made clear in a single pass drawing. The effectiveness of the proposed drawing method was verified. Furthermore, the possibility of manufacturing micro zirconia ceramic tube which could be applied to SOFC was demonstrated by applying the multi-pass drawing.

2. Basic formula of superplastic dieless drawing

The superplastic dieless drawing as shown in Fig. 2 was performed by a combination of local heating and drawing, that is tensile elongation. The local heating zone is fixed and the tube moves through the heating zone. Concurrently, the tube was

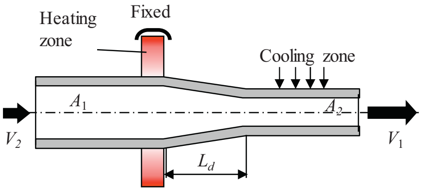

Fig. 2. Schematic illustration of superplastic dieless drawing.

subjected to tensile force and resulted elongation due to the difference in speed between drawing V_1 and feeding V_2. The reduction in area R is expressed by

$$R = 1 - A_2/A_1 = 1 - V_2/V_1\,, \tag{1}$$

based on the volume constancy law, where A_1 and A_2 are initial and deformed cross sectional area, respectively [4].

The theoretical limit of reduction in area R_c can be calculated by the difference in the flow stress between heated and cooled zone based on the equilibrium formula [9]

$$R_c = 1 - \sigma_h/\sigma_c\,, \tag{2}$$

where flow stresses at heated and cooled parts are σ_h and σ_c, respectively. From Eq. (2), it is found that the large reduction in area can be obtained because superplastic zirconia ceramic has extremely low flow stress at the heated zone and high flow stress at cooled zone.

Mean strain rate is a very important factor of superplastic deformation behaviour. The mean strain rate during dieless drawing can be calculated by relationship between the length of deformation zone in the steady state L_d and the relative speed of V_1 and V_2 as shown in following equation.

$$\dot{\varepsilon} = (V_1 - V_2)/L_d \tag{3}$$

3. Material and experimental procedure

In this study, as a representative superplastic ceramic, 3Y-TZP was employed and its tubes with outer and inner diameter of D = 6 mm and d = 4 mm were subjected to the experiment. Fig. 3 shows the schematic illustration of the proposed superplastic dieless drawing designed by authors [8]. As a heating source, an acetylene burner was introduced to obtain ultra-high temperature over 1500 °C. This heating method was effective for achieving superplastic deformation of 3Y-TZP tubes. The heating temperature was measured by a radiation thermometer. For measurement of temperature distribution, another radiation thermometer which moves together with moving tube was used. The tube was heated by the burner from one side, but the rotary tube clamp system with rotation of 120 rpm was used. A load cell with capacity of 1 kN was used for measuring drawing force. The heating temperature of 1700 °C was adjusted by controlling mixing gas ratio of acetylene and oxygen with reference to temperature of the radiation thermometer. Through the experiments, the feeding speed V_2 of 0.01, 0.05 and 0.1 mm/s was employed. The effect of drawing speed V_1, that is the elongation rate on deformation behaviour was investigated by experimental analysis.

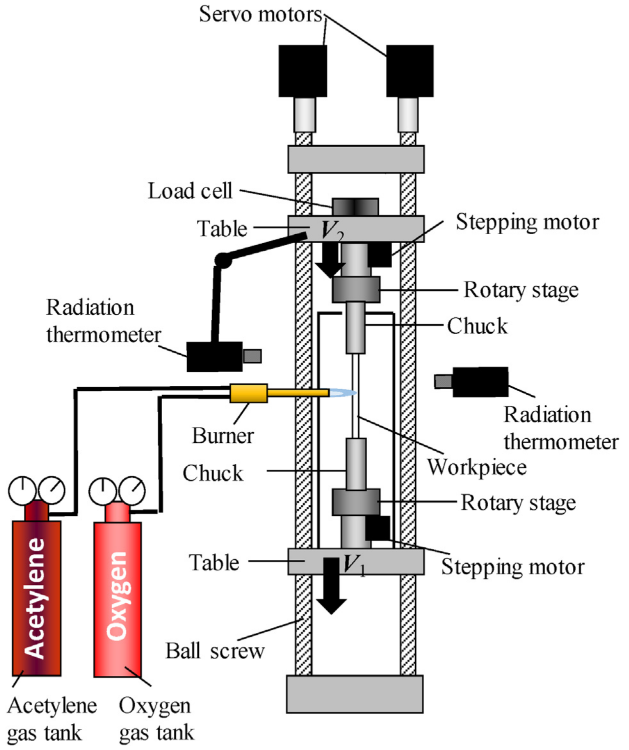

Fig. 3. Schematic illustration of superplastic dieless drawing apparatus.

4. Results and discussion

4.1. Fundamental features of superplastc dieless drawing

Fig. 4 shows the deformation features of 3Y-TZP tubes captured by a camera. The deformation mode changes from initial non-steady deformation to steady states deformation during drawing. There are the results obtained under the condition of V_2 = 0.05 mm/s and reduction in area of 70.5%. As shown in the figures, the outer diameter of the tube is reducing gradually during non-steady stage (Fig. 4(b)). In the steady stage from Fig. 4(c) to (d) (final stage), the deformation zone becomes stable. Thus, stable superplastic dieless drawing takes place. Fig. 5 shows the tube

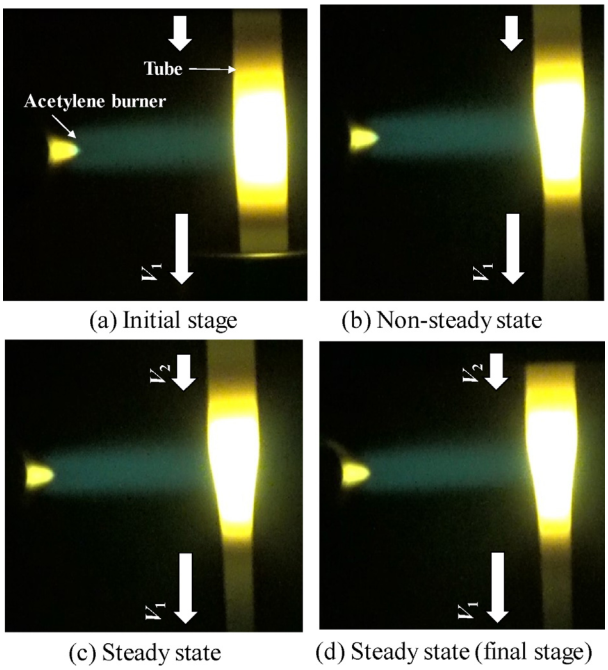

Fig. 4. Deformation transition of the ceramic tube from initial, non-steady to steady states during superplastic dieless drawing.

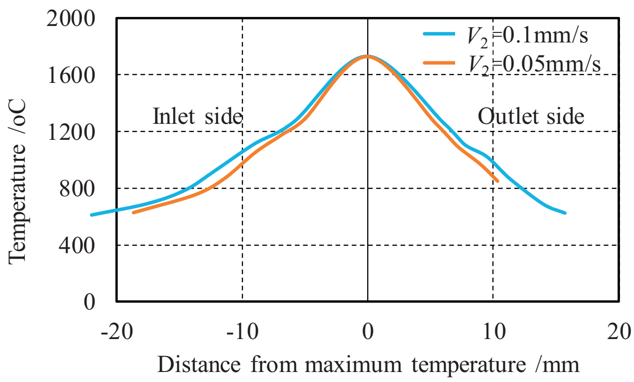

Fig. 5. Temperature distribution in superplastic dieless drawing.