Materials and Design 95 (2016) 348–357

Contents lists available at ScienceDirect

Materials and Design

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

Effect of the size of the sheet with sheared protrusions on the deformed shape after springback

Chang-Whan Lee [a,b], Dong-Yol Yang [a,*]

[a] School of Mechanical Engineering & Aerospace System, Korea Advanced Institute of Science and Technology (KAIST), 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea
[b] Fuel Cell Research Center, Korea Institute of Science and Technology (KIST), Hwarangno 14-gil 5, Seongbuk-gu, Seoul 136-791, Republic of Korea

ARTICLE INFO

Article history:
Received 12 October 2015
Received in revised form 5 January 2016
Accepted 7 January 2016
Available online 12 January 2016

Keywords:
Biaxial bending
Sheet with sheared protrusions
Metallic bipolar plate
Molten carbonate fuel cell
Hexahedral mesh coarsening

ABSTRACT

In this work, the effect of the size of a sheet with sheared protrusions on the deformed shape was investigated. After the forming process, a sheet with sheared protrusions was bent to result in specific curvatures with respect to the size of the plate due to springback. Springback deformation was assumed to be biaxial bending of an orthotropic plate. Resultant material properties of the plate were determined by using finite element analysis with hexahedral mesh coarsening. An analytic model was used to calculate deformed shapes with respect to the size of the plate. The results calculated with the proposed method showed excellent agreement with the measured results. Increasing the length in the transverse direction caused the curvature in the longitudinal direction to converge to the curvature of uniaxial bending. Increasing the length in the longitudinal direction suppressed bending in the transverse direction.

1. Introduction

Molten carbonate fuel cells (MCFCs) are high-temperature fuel cells that operate at temperatures of around 650 °C and were developed for the cogeneration of electricity and heat with its high efficiency [1–3]. A sheet with sheared protrusions is utilized for the cathode current collector and anode current collector in MCFCs [4]. The sheet with sheared protrusions forms the gas flow channel and supports other components mechanically. Fig. 1(a) shows components of MCFCs. Fig. 1(b) shows the metallic bipolar plates used in MCFCs.

The sheet with sheared protrusions is bent with a specific curvature in the direction in which trapezoidal protrusions are formed due to springback [5] as shown in Fig. 2(a). After the sheet is cut into a variety of sizes for fuel cell applications, the deformation modes change with respect to the size of the sheet with sheared protrusions. The deformed shape after springback depends on the size of the sheet with sheared protrusions after cutting. As shown in Fig. 2(b), when the sheet is cut with dimensions of 200 mm in the longitudinal direction (i.e. the lengthwise pattern-aligned direction) × 30 mm in the transverse direction (i.e. transverse to the lengthwise pattern-aligned direction), the sheet is bent in the longitudinal direction as shown in Fig. 2(b). On the other hand, when the sheet is cut with dimensions of 30 mm in the longitudinal direction × 200 mm in the transverse direction, the sheet is bent in the transverse direction as shown in Fig. 2(c).

In this work, an analytic model was employed to predict the deformed shape after springback because full simulation utilizing the simulation results of the sheared protrusions is not feasible [6]. Springback of the sheet with sheared protrusions was considered to be biaxial bending deformation of an orthotropic plate because the main deformation mode is bending deformation both in the longitudinal direction and in the transverse direction.

When a bending moment is applied to the edges of the plate in the longitudinal direction (i.e., uniaxial bending), the plate is deformed into a cylindrical shape in the longitudinal direction. At the same time, the deformation in the transverse direction shows an anticlastic curvature with the value of $\nu\kappa$, where ν is Poisson's ratio and κ is the curvature in the longitudinal direction [7]. When a bending moment is applied to the all edges of the plate (i.e., biaxial bending), the plate is deformed into a partially spherical shape, i.e. a spherical segment [8–10].

Increasing bending deformation in one direction causes the plate to deform into a cylindrical shape. Levy [11] presented a solution for biaxial bending deformation of a rectangular plate with von Karman's large deflection theory with a trigonometric series. Ashwell [12] analyzed the type of instability in large deflections of elastic plates. He investigated the characteristic instability suppressing anticlastic curvature when a flat plate is loaded by bending moments applied to all four edges. Bellow et al. [13] experimentally investigated the anticlastic behavior of flat plates and showed that the transverse distortion of a rectangular plate subjected to large longitudinal curvatures depends on the dimensionless parameter $W^2\kappa/t$, where W, κ, and t are the width, curvature, and thickness, respectively, of the plate. Pomeroy [14] investigated the effect of anticlastic bending on the curvature of beams. Pao [15] presented a

* Corresponding author.
E-mail addresses: changwhan_lee@kist.re.kr (C.-W. Lee), dyyang@kaist.ac.kr (D.-Y. Yang).

http://dx.doi.org/10.1016/j.matdes.2016.01.021
0264-1275/

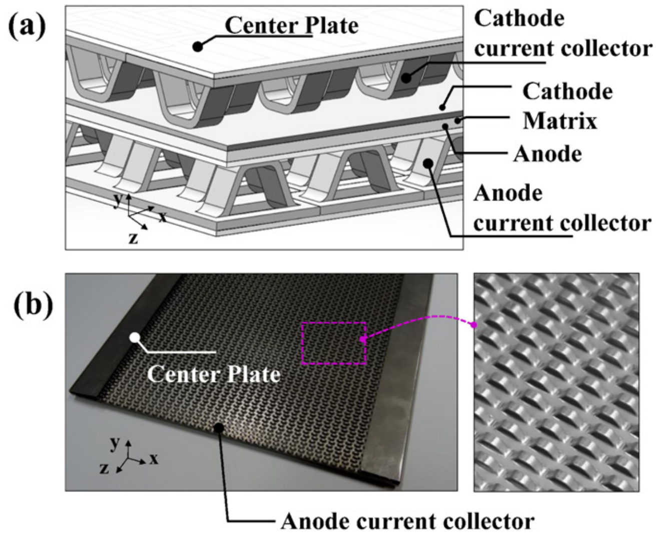

Fig. 1. Schematic figure of MCFCs: (a) components and (b) metallic bipolar plates.

closed-form solution for the problem of laminated plates subjected to simple bending of heterogeneous anisotropic plate based on the large deflection theory. Hyer and Bhavani [16] discussed the suppression of the anticlastic curvature in composite plates by using the large deflection theory analytically and experimentally with a graphite–epoxy plate and aluminum plate. Wang [17] investigated the anticlastic curvature in draw-bend springback. Gigliotti et al. [18] predicted the deformed shape and multi-stable behavior of rectangular asymmetric plates subjected to thermal and environmental loads by using the large deformation theory and Rayleigh–Ritz method. The previous studies showed that the effect of the longitudinal membrane forces on deformation becomes significant [13] and the plate is deformed into a cylindrical shape as bending deformation increases in one direction (longitudinal direction). At the same time in the transverse direction, bending deformation is suppressed, and distortion occurs.

This paper presents the effect of the size of a sheet with sheared protrusions on the deformed shape after springback. Springback deformation of the sheet with sheared protrusions was assumed to be biaxial bending of an orthotropic plate [19]. First, an analytic model for biaxial bending of an orthotropic plate was introduced. Next, the material properties of the sheet with sheared protrusions were obtained using finite element analysis [20–22] where the simulation model was constructed by using hexahedral mesh coarsening [6]. The bending moments in the longitudinal and transverse directions were obtained from the deformed shape of two specimens. Then, the deformed shape of the sheet with sheared protrusions of various dimensions was calculated by using the analytic model. To verify the proposed method, the calculated deformed shapes were compared with the measured results. Finally, characteristics of biaxial bending deformation were discussed using moment-curvature relationship.

2. Analytic model for prediction of the deformed shape after springback

2.1. Assumptions for the proposed method

A sheet with sheared protrusions undergoes large deformation during the forming process. This process also produces residual stresses that bend the sheet either in the longitudinal or in the transverse direction, as shown in Fig. 2. The main deformation modes for springback of the sheet with sheared protrusions are bending in two directions. Springback deformation of the sheet with sheared protrusions was assumed to be biaxial bending of a rectangular plate subjected to bending moments along all edges. In addition, the sheet with sheared protrusions was assumed to be an orthotropic plate [19] that has the same mechanical properties with the sheet with sheared protrusions.

In short, springback deformation of the sheet with sheared protrusions was considered to be biaxial bending of an orthotropic plate. An analytic model for biaxial bending of an orthotropic plate [12] was employed to predict the deformed shape after springback.

2.2. Biaxial bending of an orthotropic plate

Fig. 3 illustrates the biaxial bending of a plate. A bending moment in the x-direction (M_x) and a bending moment in the y-direction (M_y) are applied to the edges. If the deflection of the plate (δ) is small compared with the thickness of the plate, the bending moment in each direction and the deflection of the orthotropic plate are expressed as follows [23]:

$$M_x = \int_{-t/2}^{t/2} \sigma_{xx} z dz = -\left(D_x \frac{\partial^2 \delta}{\partial x^2} + D_{xy} \frac{\partial^2 \delta}{\partial y^2}\right), \quad M_y = \int_{-t/2}^{t/2} \sigma_{yy} z dz = -\left(D_y \frac{\partial^2 \delta}{\partial y^2} + D_{xy} \frac{\partial^2 \delta}{\partial x^2}\right) \qquad (1)$$

$$\delta(x, y) = -\frac{1}{2} \frac{M_x D_y - M_y D_1}{D_x D_y - D_1{}^2} x^2 - \frac{1}{2} \frac{M_y D_x - M_x D_{xy}}{D_x D_y - D_1{}^2} y^2 + C_1 x + C_2 y + C_3 \qquad (2)$$

where D_x, D_y, and D_{xy} are the bending moduli of the orthotropic plate and t is the thickness of the plate. C_1, C_2, and C_3 are the constants of integration. In this case, the plate is bent into a spherical shape.

If the deformation is small compared with the thickness of the plates, the effect of the longitudinal membrane forces is small. When the bending moment in the transverse direction is zero, the transverse curvature is $\nu\kappa$ due to the Poisson effect. However, as the bending moment in each direction increases, the effect of the longitudinal membrane forces becomes significant and must be considered [13]. Eq. (1) does not hold for the deformation of a plate subjected to biaxial

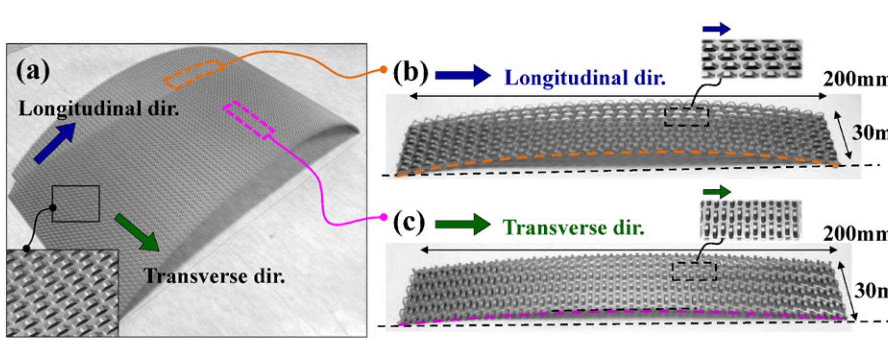

Fig. 2. Springback of the sheet with sheared protrusions and cut specimens in two major directions: (a) deformed shape of the sheet with sheared protrusions after initial cutting, (b) springback of the cut specimen aligned with the longitudinal direction, and (c) springback of the cut specimen aligned with the transverse direction.