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A New Levelling Process Using Skew-Arranged Roll Sets for the Doubly-Curved Plate

Chang-Whan Lee[1,2,#], Dong-Yol Yang[3], Hyung-Chul Ham[2], and Sung-Pil Yoon[2]

1 Department of Mechanical System and Design Engineering, Seoul National University of Science and Technology, 232 Gongneung-ro, Nowon-gu, Seoul, 01811, South Korea
2 Fuel Cell Research Center, Korea Institute of Science and Technology, 5, Hwarang-ro 14-gil, Seongbuk-gu, Seoul, 02791, South Korea
3 School of Mechanical Engineering and Aerospace System, KAIST, 291, Daehak-ro, Yuseong-gu, Daejeon, 34141, South Korea
Corresponding Author / E-mail : cwlee@seoultech.ac.kr, TEL: +82-2-970-6371, FAX: +82-2-970-5173

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In order to flatten the doubly-curved plate both in the longitudinal direction and in the transverse direction, a new levelling process using skew-arranged roll sets was proposed. The effect of the levelling process using skew-arranged roll sets was investigated with finite element analysis. Skew angle of the roll set determines the ratio of the bending moment in the longitudinal direction to the bending moment in the transverse direction. The intermesh of the roll set determines the magnitude of the deformation. Sheets with sheared protrusions, which were bent in both directions, were employed in experiments of the levelling process using skew-arranged roll sets. In the finite element analysis and experiments, bending deformation in both directions was removed at the same time by using the levelling process using two skew-arranged roll sets.

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1. Introduction

A rolled sheet can be flattened by the continuous combined bending-unbending process. During this continuous bending-unbending process, the sheet is subjected to combinations of bending and inverse bending with decreasing curvature.[1] The continuous bending-unbending process is generally referred to the levelling process.

Some defects such as curl, gutter, middle waves, and edge waves, which are due to the non-uniform distribution of residual stresses and geometrical defects, are introduced in the conventional levelling process.[2] Tension levelling is employed in the steel industry in order to remove any shape defects for rolled strips.[3] In tension levelling, some defects from the levelling process were reduced by the combination of the bending deformation and the longitudinal tension deformation.[4,5]

However, tension levelling is not appropriate for a doubly curved plate. When such a sheet is bent both in the longitudinal direction and the transverse direction, the sheet is deformed into a partially spherical shape[6,7] Continuous bending-unbending in the longitudinal direction cannot provide sufficient bending deformation in the transverse direction to flatten the sheet in the transverse direction.

The levelling process performed both in the longitudinal direction and the transverse direction can be the solution for the doubly curved plate. However, the size of the levelling device increases as the length and width of the sheet increase. In addition, the levelling process both in the longitudinal direction and the transverse direction is not appropriate to the continuous process, which combines the forming process with the levelling process.

In this study, a new levelling process using skew-arranged roll sets was introduced in order to flatten the sheet both in the longitudinal direction and in the transverse direction in a single pass. By using skew-arranged roll sets, bending moments both in the longitudinal direction and in the transverse direction are simultaneously applied to the sheet.

In the first part of this paper, the levelling process using skew-arranged roll sets was investigated with the finite element method. For simplification, an isotropic doubly curved plate was employed in the analysis. In the parameter study, the effect of major parameters, such as a skew angle and roll intermesh, was examined. In the second part of this paper, the applicability of the levelling process using skew-arranged roll sets was investigated through experiments of the doubly curved plates. For an example of the doubly curved plate, a sheet with sheared protrusions, which is used for the metallic bipolar plate in molten carbonate fuel cells (MCFCs)[8,9] and the metallic sandwich plate in lightweight products,[10] was chosen. The optimization was conducted using the response surface method.[11,12] From the finite element analysis and experiments, it was found that, the bending deformation both in the longitudinal direction and in the transverse direction was simultaneously

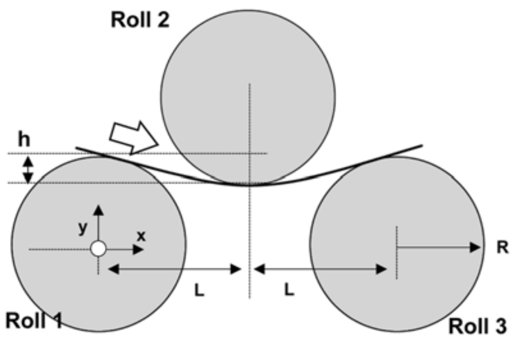

Fig. 1 Conventional levelling process using three rolls

flattened by using the levelling process with skew-arranged roll sets.

2. New Levelling Process using Skew-Arranged Roll Sets

2.1 Levelling process using skew-arranged roll sets

The conventional levelling process utilizes staggered pairs of meshing rolls. The cylindrical rolls are aligned in parallel for the levelling process. Many rolls are adjusted in order to flatten the sheet and remove the residual stress from it.[13] The levelling process using three rolls is shown in Fig 1. The roll intermesh (h) and the horizontal distance between rolls (L) are the major variables in the levelling process.

In the conventional levelling process, a moment in the longitudinal direction (levelling direction) is applied to the sheet. At the same time, a moment in the transverse direction due to Poisson's ratio is applied.[14] If the bending in the longitudinal direction is determined by the roll intermesh, the bending deformation in the transverse direction is determined by the Poisson's ratio of the material. It is difficult to control the moment in the longitudinal and the transverse directions independently. For these reasons, the conventional levelling process is not suitable to flatten the doubly curved plate effectively.

If the sheet is small, a doubly curved plate can be flattened by using the levelling process both in the longitudinal direction and the transverse direction. The residual stress and moment in the sheet can be minimized by the levelling process in both directions. However, a rolled sheet or a large sheet cannot be subjected to the levelling process both in the longitudinal direction and the transverse direction.

In this work, a new levelling process using skew-arranged roll sets was introduced to effectively flatten doubly curved plates. A schematic figure of the levelling process using two skew-arranged roll sets is shown in Fig. 2. By using the skew-arranged roll sets, bending moments both in the longitudinal direction and the transverse direction are applied to the sheet; and the moments are individually controlled by controlling the skew angle and the roll intermesh.

2.2 Effects of the skew-arranged roll sets in the levelling process

In order to investigate the effect of the skew-arranged roll set, the levelling process using one skew-arranged roll set was conducted by finite element analysis. For this finite element analysis, a doubly curved isotropic sheet was employed. The geometry of the doubly curved plate was calculated using MATLAB (v2014a, MathWorks, Natick, MA, USA). The values of the curvature in the longitudinal direction (κ_x) and in the transverse direction (κ_y) are 0.001 mm^{-1} and 0.0005 mm^{-1}, respectively. The size of the sheet is 500 mm (in the longitudinal direction) by 100 mm (in the transverse direction). The thickness of the sheet is 2.4 mm.

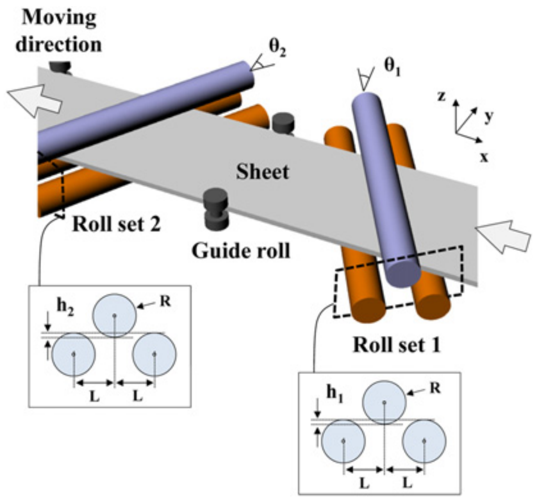

Fig. 2 Schematic figure of the levelling process for a doubly curved plate using skew-arranged roll-sets

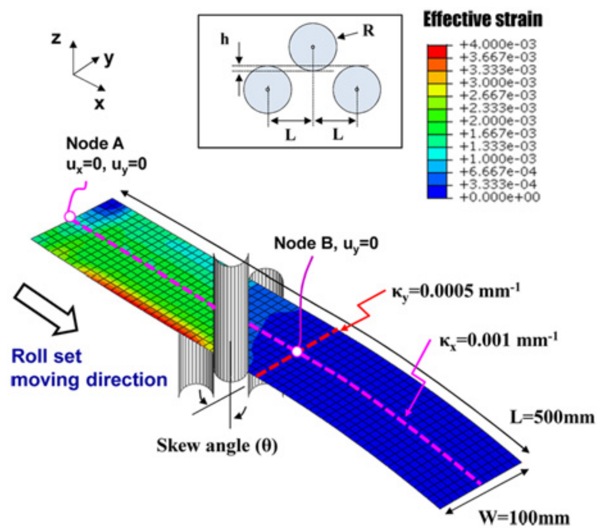

Fig. 3 Simulation model of the levelling process using one skew-arranged roll set

The simulation model is shown in Fig. 3. The elastic modulus of the sheet is 200 GPa and the yield stress is 100 MPa. The flow stress of the material is given by the relationship of $\sigma=1000(0.01+\varepsilon_p)^{0.5}$. The radius of the roll (R) is 15 mm, and the horizontal distance between the neighboring rolls (L) is 30 mm.

For the finite element analysis of the levelling process using the skew-arranged roll set, ABAQUS/Standard v6.10[15] was employed. As shown in Fig. 3, x-direction means the moving direction of the roll set and the longitudinal direction of the sheet; and y-direction means the transverse direction of the sheet. In order to describe the levelling

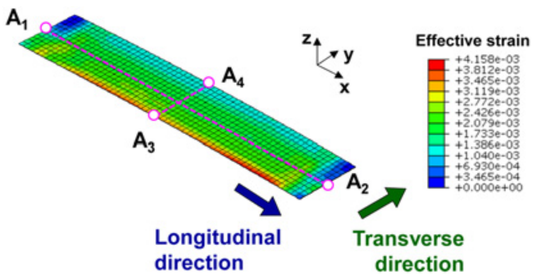

Fig. 4 Results of the levelling process using one skew-arranged roll set (h=0.6 mm, θ=45º)

process, the displacements of node A in the x-direction (u_x) and y-direction (u_y) are fixed. The y-directional displacement (u_y) of node B is fixed in order to prevent the rotation of the sheet. The roll set moves in the x-direction with a roll intermesh of h. The contact between the sheet and the roll is assumed to be governed by Coulomb friction with a frictional coefficient of 0.1. The deformed shape of the sheet was measured after springback analysis.

In the levelling process using skew-arranged roll sets, the primary process variables are the roll intermesh (h) and the skew angle (θ). Case studies were conducted in order to investigate the effects of the primary process variables (h, θ). Fig. 4 shows the simulation result when h is 0.6 mm, θ is 45º, R is 15 mm, and L is 30 mm. The results of the levelling process were evaluated using the deflection along A_1-A_2 (longitudinal direction) and along A_3-A_4 (transverse direction). In all case studies, R is fixed at 15 mm and L is fixed at 30 mm.

2.2.1 Effects of the skew angle (θ)

Fig. 5(a) shows the deformed shape of the sheet in the longitudinal direction after the levelling process using the skew-arranged roll set with respect to the skew angle (θ) when h is 0.7mm. The initial deflection of the sheet in the longitudinal direction (A_1-A_2) is 31.08mm. After the levelling process with θ of 15˚, the deflection of the sheet in the longitudinal direction is -19.91 mm. The deflection in the longitudinal direction decreases to -3.35 mm with θ of 45˚. The negative value of the deflection implies excessive bending deformation in the longitudinal direction. As the skew angle increases, the bending deformation in the longitudinal direction decreases.

In the levelling process with the skew-arranged roll set, deformation mode changes when θ is larger than zero. When θ is 0˚, the deflection of the sheet in the longitudinal direction is 0.44mm. When θ is 1˚, the deflection is -13.49mm. While the skew angle increases, the bending deformation in the longitudinal direction increases. A skew-arranged roll set (θ>0) results in more stresses in the sheet to prevent the rotation of the sheet; and more plastic deformation occurs in the longitudinal direction occurs.

Fig. 5(b) shows the deformed shape of the sheet in the transverse direction after the levelling process using skew-arranged roll set with respect to the skew angle (θ) when h is 0.7 mm. When the skew angle (θ) of the roll set is zero, the deflection in the transverse direction is not changed as shown in Fig. 5(b). It means that deformation in the transverse direction does not occur when θ is 0˚. When θ is larger than 0˚, the deflection in the transverse direction is different from the initial geometry. As the skew angle increases, the bending deformation in the transverse direction increases. The deflection in the transverse direction is distorted as shown in Fig. 5(b). Near A_3, large bending deformation in the transverse direction occurs.

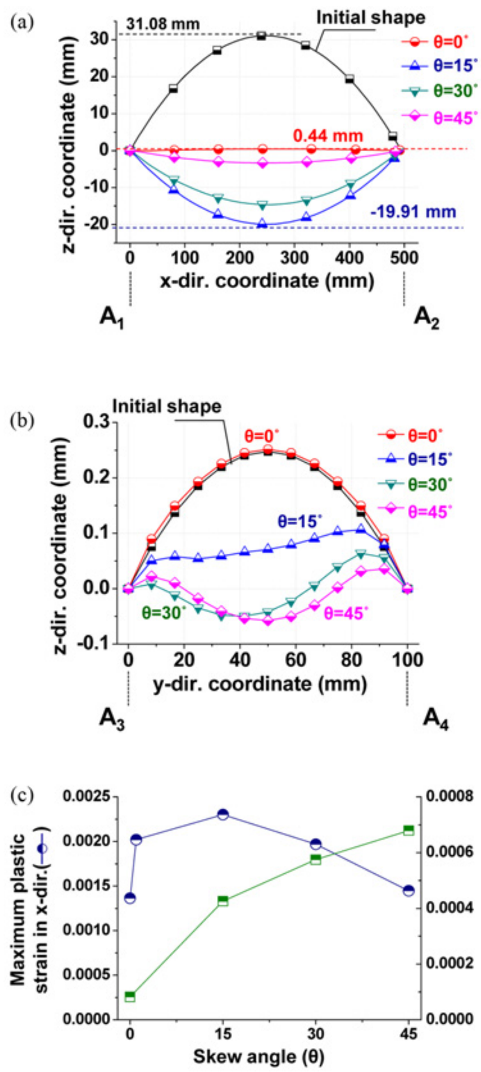

Fig. 5 Deformed shape of the sheet with respect to the skew angle (θ) along the (a) longitudinal direction (A_1-A_2) (b) transverse direction (A_3-A_4), and (c) maximum plastic strain in the x-direction and the y-direction

Fig. 5(c) shows the distribution of the maximum plastic strain in the x-direction along A_1-A_2 and the maximum plastic strain in the y-direction along A_3-A_4. As θ increases, the maximum plastic strain in the y-direction increases. At the same time, the maximum plastic strain in the x-direction decreases. These results imply that by controlling the skew angle, the ratio of the bending moment in the longitudinal direction to the transverse direction can be determined.

2.2.2 Effects of the roll intermesh (h)

Fig. 6(a) shows the deflection in the longitudinal direction (A_1-A_2) and in the transverse direction (A_3-A_4) when the skew angle (θ) is 45˚. As the roll intermesh (h) increases, the bending deformation of the sheet in the longitudinal direction increases. The initial deflection in the

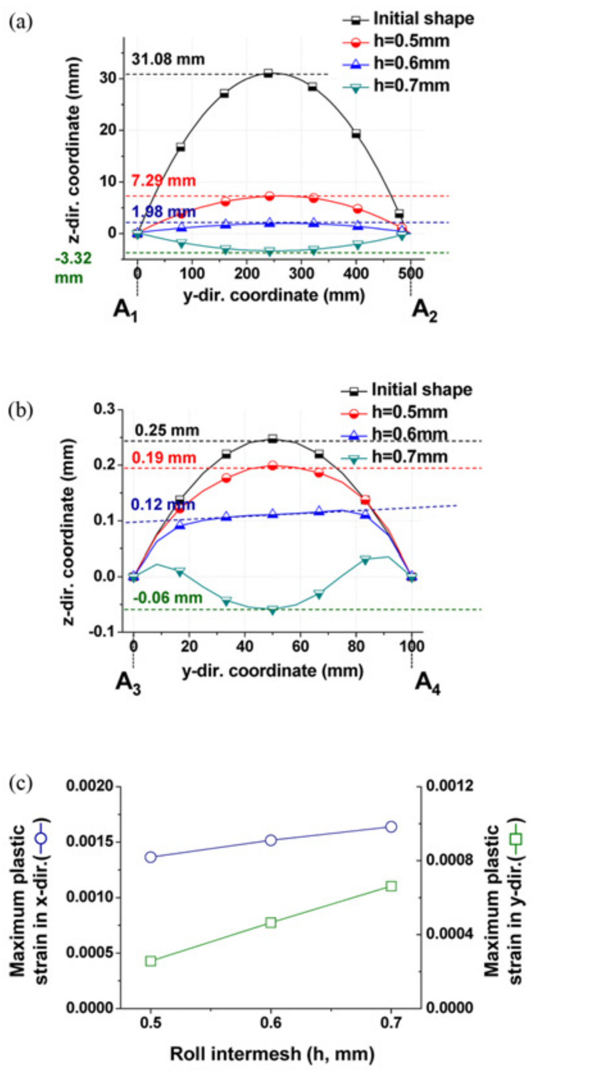

Fig. 6 Deformed shape of the sheet with respect to the roll intermesh (h), along the (a) longitudinal direction (A_1-A_2), (b) transverse direction (A_3-A_4), and (c) maximum plastic strain in x-direction and y-direction with respect to the roll intermesh (h)

longitudinal direction is 31.08 mm. When h is 0.6mm, the deflection in the longitudinal direction decreases to 1.98mm. When h is 0.7mm, the deflection in the longitudinal direction is -3.32mm. As the roll intermesh (h) increases, bending deformation in the longitudinal direction increases.

The effect of the roll intermesh (h) on the deflection in the transverse direction (A_3-A_4) is also shown in Fig. 6(b). The initial deflection in the transverse direction is 0.25mm. When h is 0.6mm, the deflection in the transverse direction decreases to 0.12mm. When h is 0.7mm, the deflection in the transverse direction decreases to 0.06mm (1/4 of the initial deflection). As the roll intermesh (h) increases, bending deformation in the transverse direction increases.

Fig. 6(c) shows the distribution of the maximum plastic strain in the x-direction along A_1-A_2 and the maximum plastic strain in the y-direction along A_3-A_4. As the roll intermesh increases, the maximum plastic strains both in the x-direction and the y-direction increase.

From these results, it can be inferred that by using the skew-

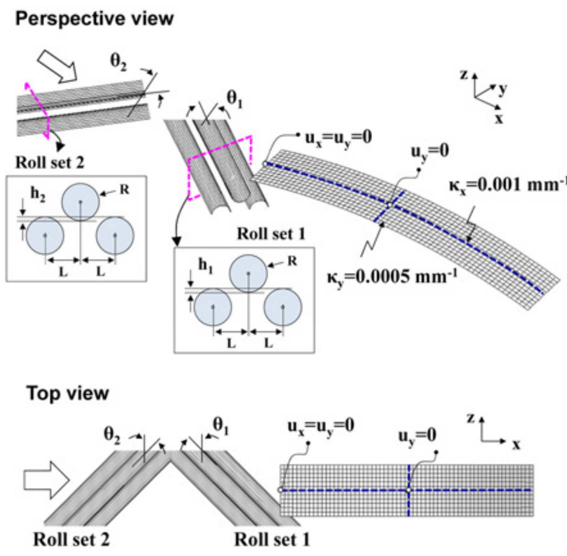

Fig. 7 Simulation model for the levelling process using two skew-arranged roll sets

arranged roll set in the levelling process, bending deformation occurs both in the longitudinal direction and the transverse direction; and the bending moment in each direction can be controlled individually. The skew angle of the roll set (θ) controls the ratio of the bending moment in the longitudinal direction to the bending moment in the transverse direction. The intermesh of the roll set (h) controls the magnitude of the deformation.

The problem of the levelling process using one skew-arranged roll set is the unbalanced distortion of the sheet, as shown in Figs. 4 and 5(b). The deformation of the sheet due to the skew-arranged roll set is not symmetric at the center. The equivalent plastic strain near A_3, where the roll first contacts the sheet, is larger than on the opposite side (A_4), because reaction forces in the transverse direction occur in order to prevent the rotation of the sheet. Asymmetric distribution of plastic deformation induces the distortion of the sheet as shown in Fig. 5(b).

The distortion of the sheet can be minimized by using two skew-arranged roll sets, as shown in Fig. 2. In the levelling process using two skew-arranged roll sets, two roll sets are not parallel. By controlling the intermesh and the skew angle of the roll sets, the plastic deformation of the sheet can be more symmetrically distributed.

2.3 Optimization of the levelling process using skew-arranged roll sets

The simulation model of the levelling process using two skew-arranged roll sets are shown in Fig. 7. In this process, the major process variables are the skew angle of the roll 1 (θ_1), the skew angle of the roll 2 (θ_2), the intermesh of the roll 1 (h_1) and the intermesh of the roll 2 (h_2). A perspective view and top view of the simulation model are shown in Fig. 7.

In the simulation model, the sheet is 500 mm (in the longitudinal direction) × 100mm (in the transverse direction). The initial values of the curvature in the longitudinal direction (κ_x) and the transverse direction (κ_y) are 0.001 mm^{-1} and 0.0005 mm^{-1}, respectively. The material properties of the sheet are identical to the sheet used in the

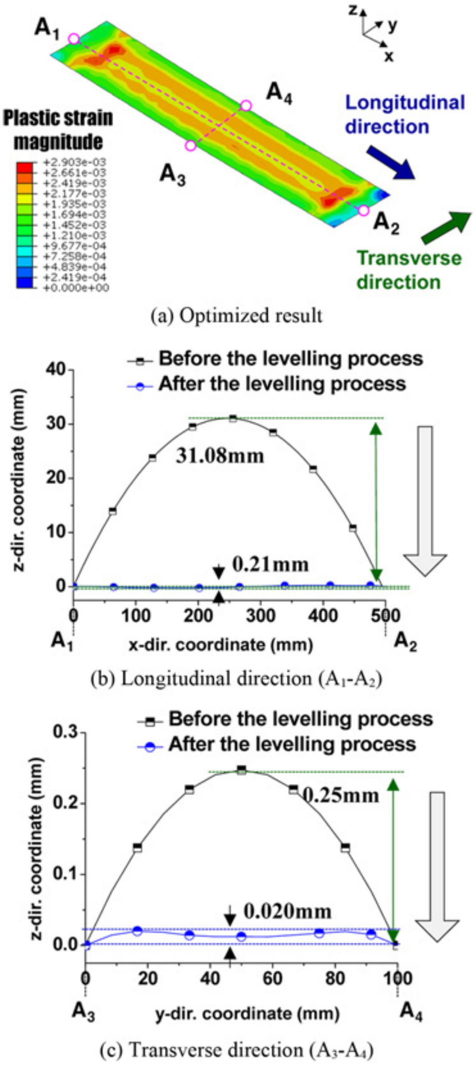

Fig. 8 Optimization result using response surface method (a) Optimization results (θ=47.03°, h_1=0.49 mm and h_2=0.60 mm) (b) Deflection in the longitudinal direction, and (c) Deflection in the transverse direction

simulation of the levelling process using one skew-arranged roll set. The radius of the rolls (R) is 15mm and the distance between the roll (L) is 30 mm.

In the previous studies,[16] the optimized levelling condition was found using the response surface method. The simulation result using the optimized condition (θ=47.03°, h_1=0.49 mm and h_2=0.60 mm) is shown in Fig. 8(a). Unlike the levelling process using one skew-arranged roll set, the plastic deformation is almost symmetric along A_1-A_2 and A_3-A_4.

The deflections of the sheet in the longitudinal direction and in the transverse direction after the levelling process are shown in Figs. 8(b) and 8(c), respectively. Prior to the levelling process, the deflection of the sheet is 31.08 mm. After the levelling process using the optimization levelling condition, the deflection of the sheet is 0.21 mm (1/151 of the initial deflection). At the same time, the deflection in the transverse direction also reduced to 0.020 mm (1/13 of the initial deflection). The deflection in the transverse direction after the levelling process is shaped

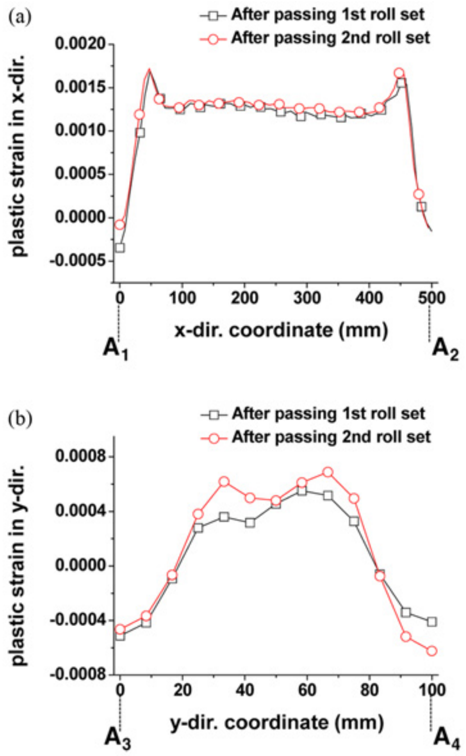

Fig. 9 Plastic strain distribution after passing first roll set and second roll set (a) plastic strain in the x-direction along A_1-A_2 and (b) plastic strain in the y-direction along A_3-A_4

like an inverse 'W', because the bending deformation did not occur at the boundary of the sheet. By using two skew-arranged roll sets, the sheet is almost straightened both in the longitudinal direction and the transverse direction.

Fig. 9(a) shows the plastic strain distribution strain after passing the first roll set and after passing the second roll set in the x-direction along A_1-A_2. After passing the second roll set, the plastic strain in in the x-direction increases slightly. The second roll set has little effect on the deformation in the longitudinal direction.

On the contrary, the second roll set has a significant effect on the plastic strain distribution in the y-direction. Fig. 9(b) shows the plastic strain distribution after passing first roll set and after passing second roll set in the y-direction along A_3-A_4. After passing the first roll set, the plastic strain in the y-direction is not symmetric at the center. It results in the unbalanced distortion of the sheet. After passing the second roll set, the plastic strain in the y-direction was changed to symmetrical deformation. The bending deformation in the transverse direction and the distortion of the sheet was minimized by using two skew-arranged roll sets.

3. Experiments with the Levelling Process Using Skew-Arranged Roll Sets

3.1 A sheet with sheared protrusions

In this work, a sheet with sheared protrusions was selected as an example of the doubly curved plate, because manufacturing of the

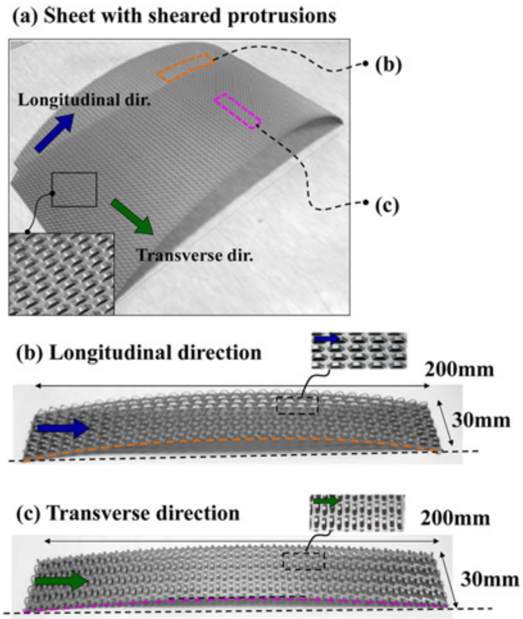

Fig. 10 Deformation of the sheet after cutting (a) Current collector after springback (b) 200 mm in the longitudinal direction × 30 mm in the transverse direction, and (c) 30 mm in the longitudinal direction × 200 mm in the transverse direction (Adapted from Ref. 21 with premission)

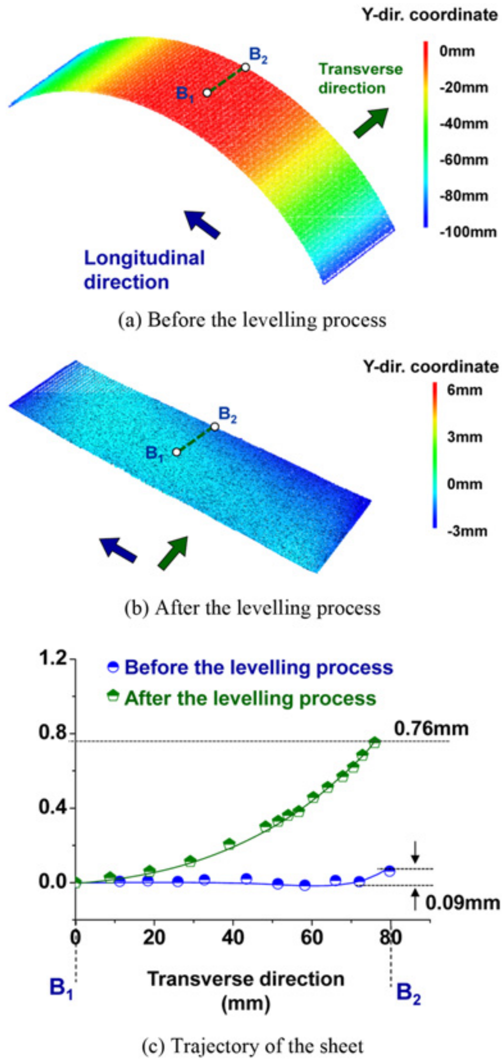

Fig. 11 Results of the three-dimensional scanning (a) before the levelling process (b) after the levelling process, and (c) Deformed shape of the sheet in the transverse direction (B_1-B_2)

doubly curved plate is not a simple work.[17,18] A sheet with sheared protrusions is utilized for the current collector in molten carbonate fuel cells (MCFCs).[19] A sheet with sheared protrusions is manufactured from the three-stage forming process such as the slitting process, the preforming process, and the final forming process.[20] In the slitting process, the sheet is formed with sheared protrusions of low height. In the preforming process, the sheet is stretched to the shape of the preform in order to minimize local deformation. In the final forming process, the sheet is formed with sheared protrusions of a taller height.

Owing to the residual stress induced during the three-stage forming process, the sheet with sheared protrusions is bent with a specific curvature in the direction in which the trapezoidal protrusions are formed,[8] as shown in Fig. 10(a). The deformation modes of the sheet after springback change with respect to the size of the sheet with sheared protrusions. When the length in the longitudinal direction (i.e., the lengthwise pattern-aligned direction) is longer (Fig. 10(b)), the sheet with sheared protrusions is bent in the longitudinal direction. When the length in the transverse direction (i.e., transverse to the lengthwise pattern-aligned direction) is longer (Fig. 10(c)), the sheet with sheared protrusion is bent in the transverse direction. It means that springback deformation of the sheet with sheared protrusions is biaxial bending deformation of a rectangular plate.[21]

Lee et al.[8] designed the levelling process using three rolls for a sheet with sheared protrusions. A sheet with sheared protrusions was flattened in the longitudinal direction with three rolls. Figs. 11(a) and 11(b) show the external geometries of the sheet with sheared protrusions measured using an optical 3D scanner (ATOS III Triple Scan, GOM mbH). In these experiments, the dimension of the sheet with sheared protrusion is 530 mm in the longitudinal direction and 160 mm in the transverse direction. Before the levelling process, the deflection in the longitudinal direction is 93.45 mm. After the levelling process, the deflection in the longitudinal direction decreases to 1.04 mm.

The conventional levelling process has negative effect on the deformation in the transverse direction. The deformed shape of the sheet along B_1-B_2 is shown in Fig. 11(c). Before the levelling process, the maximum deflection in the transverse direction is 0.09 mm. The bending deformation in the transverse direction is suppressed, because the curvature in the longitudinal direction is the principal curvature.[21] After the levelling process, the sheet with sheared protrusion is bent in the transverse direction, as shown in Fig. 11(c), because the moment in the longitudinal direction is eliminated by the levelling process. The deflection in the transverse direction increases to 0.76 mm.

The bending deformation in the transverse direction still remains after the levelling process. The sheet is flattened only in the longitudinal direction after the conventional levelling process. In order to straighten the sheet with sheared protrusion both in the longitudinal direction and the transverse direction, the levelling process using skew-arranged roll sets was applied to the sheet with sheared protrusions.

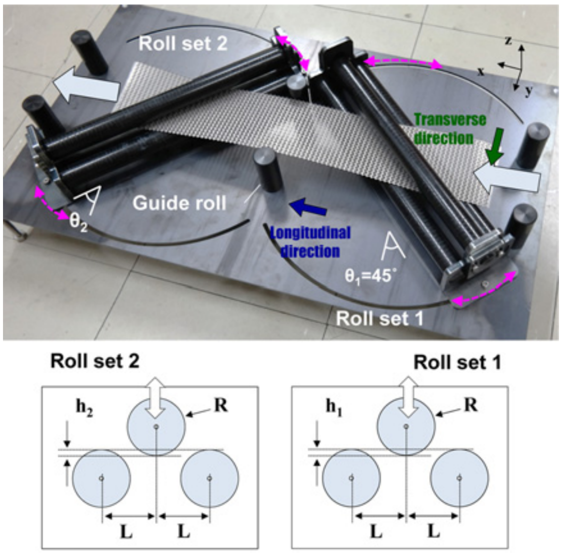

Fig. 12 Experimental set-up for the levelling process using two skew-arranged roll sets

3.2 Experimental set-up

The experimental set-up for the levelling process using two skew-arranged roll sets is shown in Fig. 12. The rolls in each roll set are aligned in parallel. The lower rolls in the roll set are fixed and the intermesh of the upper roll is adjusted by moving the upper roll. The skew angle of the roll set (θ_1, θ_2) can be adjusted by rotating roll sets. The roll sets can be skew-arranged to the desired skew angle.

The radius of rolls (R) is 15 mm and the horizontal distance between rolls (L) is 30 mm. The radius of guide rolls is 15 mm. The guide rolls can be skew-arranged idly. Six guide rolls are employed to move the sheet in the desired direction (longitudinal direction). In the experiments, the size of the sheet with sheared protrusions is 530 mm (longitudinal direction) by 100 mm (transverse direction).

The sheet with sheared protrusions was considered as an orthotropic plate. Material properties of the sheet with sheared protrusions were obtained using finite element analysis where the simulation model was constructed by using hexahedral mesh coarsening.[21] Table 1 gives the homogenized resultant material properties of the sheet with sheared protrusions.

Table 1 Homogenized resultant material properties of the sheet with sheared protrusions (L means the longitudinal direction and T means Transverse direction)

E_L (GPa)	E_T (GPa)	G_{LT} (GPa)	ν_{LT}
13.21	5.83	1.4	0.22
D_L (N·mm^2/mm)	D_T (N·mm^2/mm)	D_{LT} (N·mm^2/mm)	t (mm)
1163.25	406.61	116.75	2.4

Table 2 Design of experiments for the sheet with sheared protrusions

Case	θ_2 (°)	h_1 (mm)	h_2 (mm)	$\|e_1\|$	$\|e_2\|$
1	40	2	3.5	0.077	0.490
2	40	1.5	3	0.304	0.190
3	40	2.5	3	0.010	0.342
4	40	2	2.5	0.108	0.420
5	45	1.5	2.5	0.124	0.526
6	45	1.5	3.5	0.402	1.458
7	45	2	3	0.072	0.424
8	45	2.5	3.5	0.454	1.640
9	45	2.5	2.5	0.015	0.360
10	50	1.5	3	0.013	0.490
11	50	2.5	3	0.072	0.482
12	50	2	2.5	0.077	0.536
13	50	2	3.5	0.097	0.490

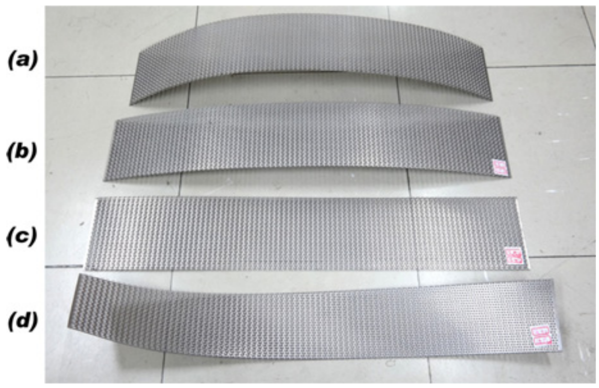

Fig. 13 Experimental results: (a) Before the levelling process, (b) Insufficient deformation (Case 2, θ_2=40°, h_1=1.5 mm, h_2=3 mm), (c) optimized result (θ_2=41°, h_1=2.47 mm, h_2=3.06 mm), and (d) Excessive deformation (Case 8, θ_2=45°, h_1=2.5 mm, h_2=3.5 mm)

4. Levelling Process of the Sheet with Sheared Protrusions: Results and Discussion

The main process variables are the skew angle of roll 1 (θ_1), the skew angle of roll 2 (θ_2), the intermesh of roll 1 (h_1) and the intermesh of roll 2 (h_2). As in the previous section, the skew angle of roll set 1 (θ_1) is fixed to 45° for the simplification of the experiment.

The experiments were designed using the response surface method.[11] From the preliminary experiments,[16] the levels of three variables were determined as described in Table 2. The results of the experiments were evaluated using the ratio of the deflection in the longitudinal direction (e_1) and the ratio of the deflection in the transverse direction (e_2). The ratio of the deflection in the longitudinal direction (e_1) is $\Delta z_1/z_{LD}$ where Δz_1 is the deflection in the longitudinal direction after the levelling process and z_{LD} is the initial deflection of the sheet with sheared protrusions in the longitudinal direction (93.4mm). The ratio of the deflection in the transverse direction (e_2) is $\Delta z_2/z_{TD}$ where Δz_2 is the maximum deflection in the transverse direction after the levelling process and z_{TD} is the initial deflection of the sheet with sheared protrusions in the transverse direction (0.76 mm).

In the optimization using response surfaces, terms such as θ_2, h_1, h_2, $\theta_2 h_1$, $\theta_2 h_2$, $h_1 h_2$, θ_2^2 h_1^2 and h_2^2 are used. Using the response surface method and the results of 13 experiments (Table 2), the optimization result (θ_2=41°, h_1=2.47 mm, h_2=3.06 mm) was predicted to give minimized values of $|e_1|$ and $|e_2|$.

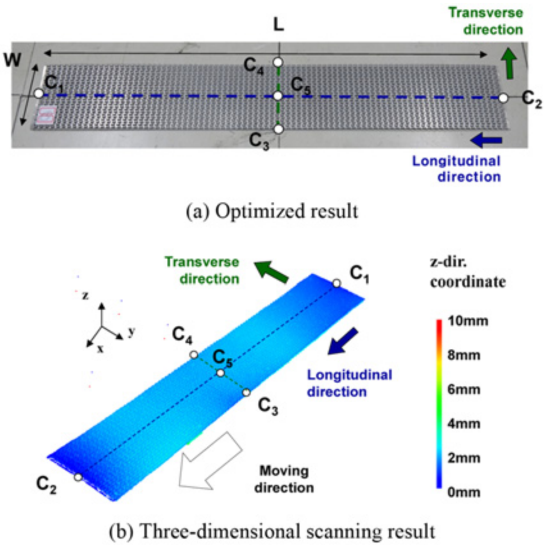

Fig. 14 Optimized results: (a) The sheet with sheared protrusions after the levelling process, and (b) three-dimensional scanning result after the levelling process

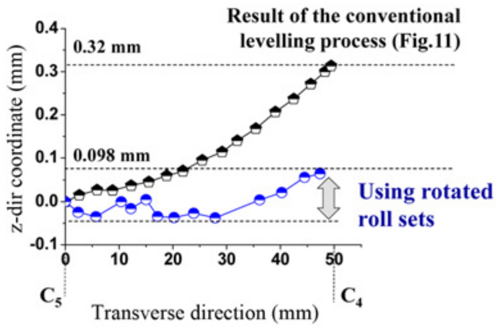

Fig. 15 Deformed shape of the sheet with sheared protrusions in the transverse direction (C_5-C_4)

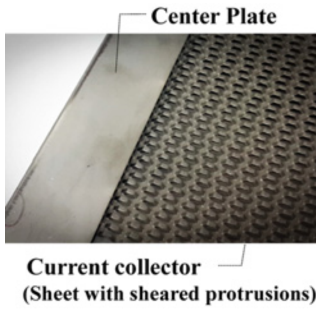

Fig. 16 Assembled unit cell of MCFCs

For comparison with other cases, some experimental results are shown in Fig. 13. Fig. 13(a) shows the initial sheet with sheared protrusion before the levelling process. The deflection in the longitudinal direction is 93.4 mm. When the bending deformation in the levelling process is insufficient (Case 2, θ_2=40°, h_1=1.5 mm, h_2=3 mm), the bending deformation in the longitudinal direction remains as shown in Fig. 13(b). Fig. 13(c) shows the optimized result (θ_2=41°, h_1=2.47 mm, h_2= 3.06 mm). In this case, the sheet with sheared protrusions is straightened both in the longitudinal direction and the transverse direction. When the bending deformation is excessive (Case 8, θ_2=45°, h_1=2.5 mm, h_2=3.5 mm), the sheet is distorted and bent as shown in Fig. 13(d).

In order to investigate the optimized results, the sheet with sheared protrusions shown in Fig. 14(a) was measured using an optical 3D scanner (ATOS III Triple Scan, GOM mbH) after the levelling process using skew-arranged roll sets (θ_2=41°, h_1=2.47 mm, h_2=3.06 mm). The three-dimensional scanning result is shown in Fig. 14(b). Before the levelling process, the maximum deflection of the sheet with sheared protrusions in the longitudinal direction (C_1-C_2) is 93.4 mm. After the levelling process using skew-arranged roll sets, the maximum deflection in the longitudinal direction is decreased to 1.39 mm (1/67 of the initial deflection).

By using the skew-arranged roll sets, the doubly curved plate can be flattened both in the longitudinal direction and the transverse direction. Fig. 15 shows the deformed shape of the sheet with sheared protrusions in the transverse direction (C_5-C_4). The maximum deflection of the sheet after the levelling process using conventional levelling process is 0.32 mm; and the bending deformation in the transverse direction remains. After the levelling process using skew-arranged roll sets (θ_2= 41°, h_1=2.47 mm, h_2=3.06 mm), the maximum deflection in the transverse direction decreases to 0.098 mm. The bending deformation in the transverse direction was greatly reduced.

After the levelling process using two skew-arranged roll sets, the flattened sheet with sheared protrusions is cut to the size of the unit cell of MCFCs and assembled successfully, as shown in Fig. 16. By flattening the sheet with sheared protrusions, uniform contact can be secured. This contact can reduce the stress concentration on the fuel cell and increase the long-term operation capability.

From the manufacturing viewpoint, the levelling process using skew-arranged roll sets has a number of advantages. The forming process of the metallic sheet can be integrated with the levelling process using the skew-arranged roll sets. After the forming process of the metallic sheets or plates, they can be bent either in the longitudinal direction or in the transverse direction. Formed products move in the forming direction; and the levelling process using skew-arranged roll sets can be directly conducted after the forming process. By integrating the levelling process and the forming process, the springback deformation occurring in the forming process can be reduced both in the longitudinal direction and the transverse direction by the levelling process.

In this work, the optimized levelling condition was found by using the response surface method because determining the process variables. The bending rigidity of the formed product depends on the forming process, the formed geometry[22,23] and curvature after springback.[24] In addition, variables of the levelling process using skew-arranged roll sets such as roll intermeshes and skew angles are highly coupled. In order to expand the applicability of the proposed levelling process, it is necessary to find out the relationship between the skew angle of the roll set (θ) and the ratio of the bending moment in the longitudinal direction. Also a new method for calculating optimized process variables and the relationship among process variables and the formed sheet is required.

5. Conclusion

A new levelling process using skew-arranged roll sets has been proposed in order to straighten a doubly curved plate. From the finite element simulation, the effects of the skew angle and the roll intermesh on the levelling process were investigated. The skew angle of roll sets controls the ratio of the bending moment in the longitudinal direction to the bending moment in the transverse direction. The intermesh of roll sets controls the magnitude of the deformation. In addition, using two skew-arranged roll sets results in minimized distortion of the sheet.

In the experiments, a sheet with sheared protrusions was selected as an example of the doubly curved plate which is used in MCFCs as a current collector. The optimized variables of the levelling process were found using the response surface method. In the experiments, the deflection both in the longitudinal direction and the transverse direction decreased. The deflection in the longitudinal direction decreased from 93.4 mm to 1.39 mm. In addition, the deflection in the transverse direction decreased from 0.32 mm to 0.098 mm. By using the levelling process with two skew-arranged roll sets, the bending deformation in the longitudinal direction and in the transverse direction was simultaneously flattened.

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REFERENCES

1. Lange, K., “Handbook of Metal Forming,” McGraw-Hill, pp. 19.44-19.47, 1985.
2. Doege, E., Menz, R., and Huinink, S., “Analysis of the Levelling Process based Upon an Analytic Forming Model,” CIRP Annals-Manufacturing Technology, Vol. 51, No. 1, pp. 191-194, 2002.
3. Morris, J. W., Hardy, S. J., and Thomas, J. T., “Some Fundamental Considerations for the Control of Residual Flatness in Tension Levelling,” Journal of Materials Processing Technology, Vol. 120, No. 1, pp. 385-396, 2002.
4. Huh, H., Lee, H. W., Park, S. R., Kim, G. Y., and Nam, S. H., “The Parametric Process Design of Tension Levelling with an Elasto-Plastic Finite Element Method,” Journal of Materials Processing Technology, Vol. 113, No. 1, pp. 714-719, 2001.
5. Li, S.-Z., Yin, Y.-D., Jie, X., Hou, J.-M., and Yoon, J., “Numerical Simulation of Continuous Tension Leveling Process of Thin Strip Steel and Its Application,” Journal of Iron and Steel Research, International, Vol. 14, No. 6, pp. 8-13, 2007.
6. Ashwell, D. G., “A Characteristic Type of Instability in the Large Deflexions of Elastic Plates. I. Curved Rectangular Plates Bent about One Axis. II. Flat Square Plates Bent about all Edges,” Proc. of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, Vol. 214, No. 1116, pp. 98-118, 1952.
7. Cai, Z.-Y., Li, L.-L., Wang, M., and Li, M.-Z., “Process Design and Longitudinal Deformation Prediction in Continuous Sheet Metal Roll Forming for Three-Dimensional Surface,” Int. J. Precis. Eng. Manuf., Vol. 15, No. 9, pp. 1889-1895, 2014.
8. Lee, C.-W., Yang, D.-Y., Kang, D.-W., and Lee, T.-W., “Study on the Levelling Process of the Current Collector for the Molten Carbonate Fuel Cell based on Curvature Integration Method,” International Journal of Hydrogen Energy, Vol. 39, No. 12, pp. 6714-6728, 2014.
9. Kim, H., Bae, J., and Choi, D., “An Analysis for a Molten Carbonate Fuel Cell of Complex Geometry using Three-Dimensional Transport Equations with Electrochemical Reactions,” International Journal of Hydrogen Energy, Vol. 38, No. 11, pp. 4782-4791, 2013.
10. Besse, C. C. and Mohr, D., “Plasticity of Formable All-Metal Sandwich Sheets: Virtual Experiments and Constitutive Modeling,” International Journal of Solids and Structures, Vol. 49, No. 19, pp. 2863-2880, 2012.
11. Arora, J. S., “Introduction to Optimum Design,” Academic Press, 2nd Ed., pp. 733-741, 2004.
12. Jeong, H.-S. and Cho, J.-R., “Bent Tube Design Used in a High Temperature Heat Exchanger using a FE Analysis and RSM,” Int. J. Precis. Eng. Manuf., Vol. 14, No. 12, pp. 2119-2125, 2013.
13. Madej, L., Muszka, K., Perzyński, K., Majta, J., and Pietrzyk, M., “Computer Aided Development of the Levelling Technology for Flat Products,” CIRP Annals-Manufacturing Technology, Vol. 60, No. 1, pp. 291-294, 2011.
14. Timoshenko, S. P. and Woinowsky-Krieger, S., “Theory of Plates and Shells,” McGraw-Hill, 2nd Ed., pp. 364-375, 1959.
15. Dassault Systèmes, Abaqus 6.10, Analysis User’s Manual, 2010. abaqusdoc.ucalgary.ca/pdf_books/ANALYSIS_1.pdf (Accessed 2 AUG 2016)
16. Lee, C.-W., “Investigation into the Mechanical Behavior and the Levelling Process of the Sheet with Sheared Protrusions for Fuel Cell Application,” Ph.D. Thesis, Department of Mechanical Engineering, KAIST, 2014.
17. Park, J.-W., Kim, Y.-B., Kim, J., and Kang, B.-S., “Study on Multiple Die Stretch Forming for Curved Surface of Sheet Metal,” Int. J. Precis. Eng. Manuf., Vol. 15, No. 11, pp. 2429-2436, 2014.
18. Shim, D.-S. and Yang, D.-Y., “Multi-Stage Forming using Optimized Preform in the Line Array Roll Set Process and Its Industrial Application,” Int. J. Precis. Eng. Manuf., Vol. 15, No. 10, pp. 2085-2092, 2014.
19. Yuh, C., Colpetzer, J., Dickson, K., Farooque, M., and Xu, G., “Carbonate Fuel Cell Materials,” Journal of Materials Engineering and Performance, Vol. 15, No. 4, pp. 457-462, 2006.
20. Yang, D.-Y., Lee, C.-W., Kang, D.-W., Chang, I.-G., and Lee, T.-W., “Optimization of the Preform Shape in the Three-Stage Forming Process of the Shielded Slot Plate in Fuel Cell Manufacturing,”

Proc. of the 11th International Conference on Numerical Methods in Industrial Forming Processes, pp. 446-451, 2013.

21. Lee, C.-W. and Yang, D.-Y., "Effect of the Size of the Sheet with Sheared Protrusions on the Deformed Shape after Springback," Materials & Design, Vol. 95, pp. 348-357, 2016.

22. Wang, W., Sun, X., and Wei, X., "Integration of the Forming Effects into Vehicle Front Rail Crash Simulation," International Journal of Crashworthiness, Vol. 21, No. 1, pp. 9-21, 2016.

23. Tekkaya, A. E., Allwood, J. M., Bariani, P. F., Bruschi, S., Cao, J., et al., "Metal Forming beyond Shaping: Predicting and Setting Product Properties," CIRP Annals-Manufacturing Technology, Vol. 64, No. 2, pp. 629-653, 2015.

24. Pomeroy, R. J., "The Effect of Anticlastic Bending on the Curvature of Beams," International Journal of Solids and Structures, Vol. 6, No. 2, pp. 277-285, 1970.