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Analysis and Experiment on Incremental Forming Process for the Spiral Plate of Continuous Screw Conveyer

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Abstract: An incremental press-forming method was newly developed for the fabrication of spiral plates of a continuous screw conveyer, boring screw, screw pump and so on. In this method, a pair of V-shaped punches and dies with two opposite inclined edges are used instead of punch and die with spiral surfaces. The experiments on incremental forming were carried out on aluminum alloy and steel disks with a hole and a slit, and the deformation process of the plate during and after the press-forming was simulated by a finite element method (FEM). The press-forming shows that the spiral plate has a correct shape and smooth surface, i. e. the gradient of the surface along the internal, central, and external spiral curves of the deformed disk is constant. In addition, the spiral pitch and the amount of spring back obtained by the FEM simulation agree well with the experimental values for the different die or punch angles, the disk thicknesses and the disk materials. The FEM calculation also indicates that the equivalent stress during the press forming as well as the residual stress after the spring back takes a maximum value at an internal diameter position where the die or punch makes first contact to the disk.

Keywords: Continuous screw conveyer, spiral plate, incremental forming, press experiment, FEM analysis, aluminum alloy, steel

1 Introduction

In the fields of sheet metals making, incremental forming is effective for increasing the flexibility of production method [Tanaka, Nakamura, Hayakawa, Nakamura and Motomura (2005); Ambrogio (2005); Allwood and Utsunomiya (2006); Suzuki, Sano and Takashina (2010)]. On the other hand, numerical simulation mainly by FEM shows the effects of the method on formability and spring back which are essential for decreasing cost, shortening time and improving quality of the production

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[Kawka and Makinouchi (1995); Morestin, Boivin and Silva (1996); Lee and Yang (1998); Saito, Takeda, Tokura and Hagiwara (2009)].

Fig.1(a) shows a continuous screw conveyer. It is made of spiral plates as shown in Fig.1(b) which are welded to a shaft. The spiral plate is made of disk with a hole and a slit as shown in Fig.1(c) through punch and die with spiral surfaces [Sato, Mibe, Obata, Tai, Takaishi and Tanaka (2000); Takaishi (2005)]. However, an expensive multi-axial machining center is needed to make punches and dies and it is time cosuming. Furthermore, a pair of punch and die can only be used for one type of spiral plates. So this method is not suitable for small batch production of various kinds of spiral plates.

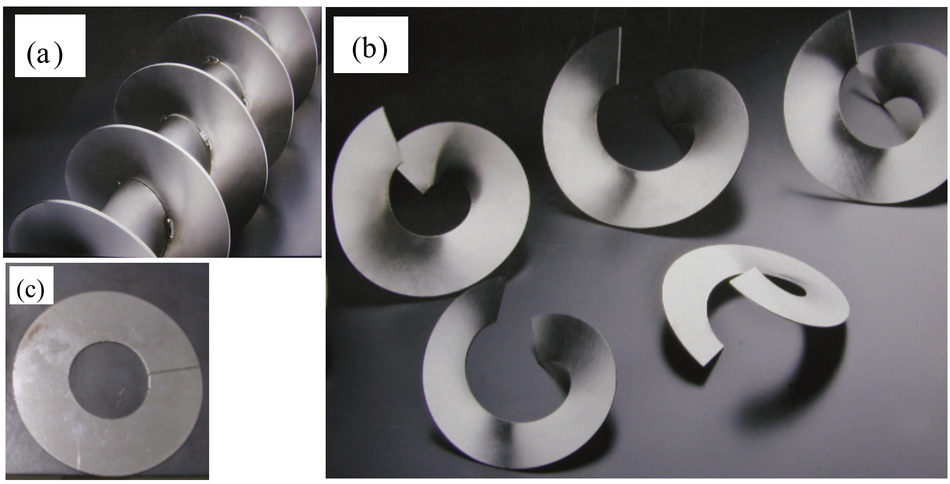


Figure 1: Specimens: screw (a), spiral plates (b) and disk with a hole and a slit (c)

In this research, an incremental press-forming method is developed to fabricate the spiral plates of a screw conveyer, boring screw, screw pump and so on. A pair of V-shaped punches and dies with two opposite inclined edges are used instead of punch and die with spiral surfaces. This method has following advantages: (1) Simple shapes of the punches and dies. (2) The punches and dies are easy to make without a need of large-scale press machine. This is possible because the requested press load is small. There is no need for machining internal diameter of the finished spiral plate, as deformation of the internal diameter is uniform and can be prospected correctively from the diameter of hole of the flat disk and pitch of the spiral plate. (3) Spiral plates of various pitches can be modified easily by changing inclination angles of the punch and die to cater for different applications. This method was used in the authors' patent on a bending machine of spiral plates and developed adjustable punches and dies for a press-forming machine of the spiral plates [Nogi (2009); Gao and Nakasa (2010)].

However, because the effects of thickness and material properties (spring back) of the plate, it takes time and material for trial manufacture of the spiral plates. In order to predict the damages to the surface, it is necessary to measure stress and strain during pressing and residual stress and strain after pressing. In this research, the deformation process of the plate during and after the incremental press-forming was simulated by FEM and a data processing software developed by the authors. Maximum equivalent stress/strain and residual stress/strain in the plate, as well as the relationships among the spiral pitch to inclination angle of the punch and die, material properties and thickness of the plate are also investigated.

2 Principle of the incremental forming method and press experiment

As shown in Fig.2, the spiral plate is made by a pair of simple punches and dies. The heads of the punches and dies are in a shape of half-cylinder. Lines AB and CD are the top lines of two dies, and M_1 and M_2 are middle points of AB and CD which are at the same level. Bottom lines of two punches are parallel to lines AB and CD respectively. As shown in Fig.3(a), two punches and dies have opposite inclination angles, $+\theta$ and $-\theta$, on the vertical plane. The angle between two punches or dies on the level plane is α as shown in Fig.3(b). Through pressing multiple places in sequences on the disk plate as shown in Fig.4, a smooth spiral plate can be made. For example, if α is 30°, 12 times of presses are carried from Position 1 to Position 12 as shown in Fig.5.

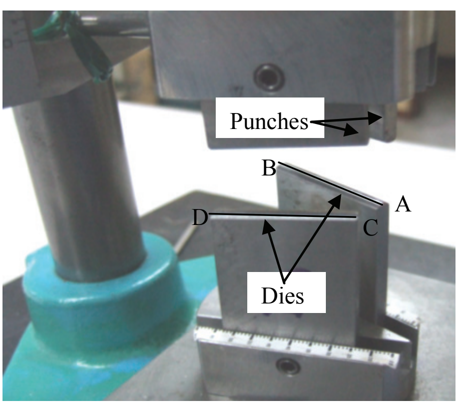


Figure 2: A pair of punches and dies

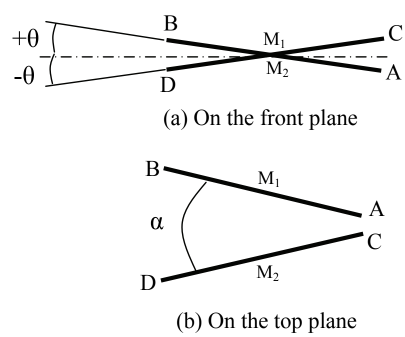


Figure 3: Angles formed by the punches and dies on the front plane (a) and top plane (b)

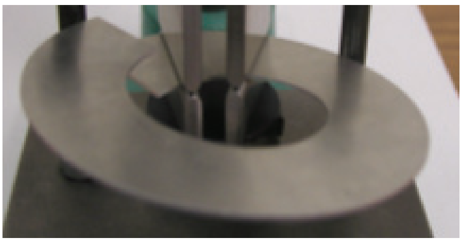


Figure 4: One press on a disk

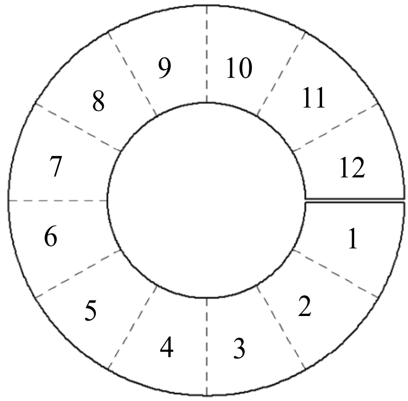


Figure 5: A sequence of positions for press operations

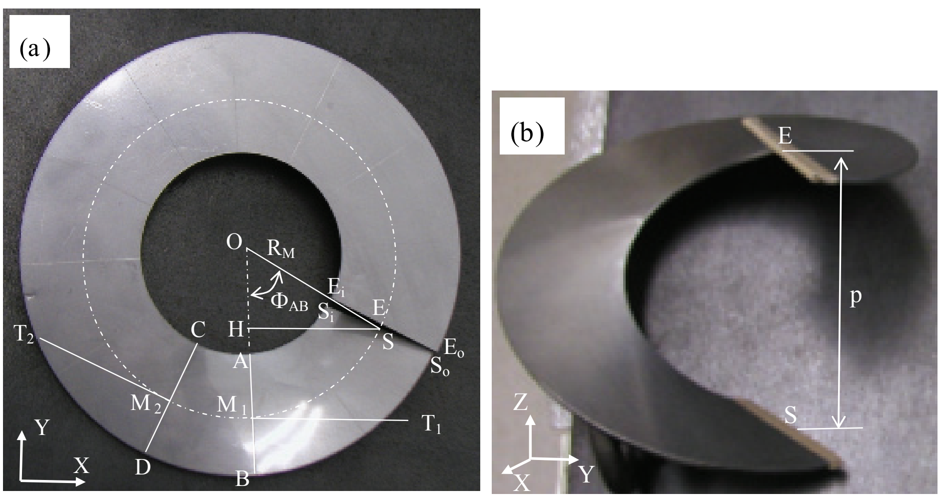


Figure 6: Deformation of the disk at the third press (a) and the last press (b)

Fig.6(a) shows the deformation of the disk at the third press. B and C are initial contact points between the dies and the disk, A and D are initial contact points between two punches and the disk, M_1 and M_2 are middle points of lines AB and CD, S and E are middle points of two edges of the slit, M_1T_1 and M_2T_2 are tangential lines of middle circle (average radius R_M) at points M_1 and M_2, Φ_{AB} is circumferential angle from the slit to line AB, where Φ_{AB}=60°. At first, the disk plate is placed on the dies manually and is supported at points B and C. With increasing press distance of the punches, the contacts between the punches and the disk start from points A and D to points B and C on the top surface. At the same time, contacts between the dies and the disk start from points B and C to points A and D on the bottom surface, and the part of disk between AB and CD is bent to form spiral shape. Meanwhile, points S and E turn around lines M_1T_1 and M_2T_2 respectively. Although points M_1 and M_2 are the same height, the displacements of points S and E are opposite, and the distance between them increases. For the given inclination angle θ of the punches and dies, the displacement of point S in axial direction of the spiral surface (Z axial direction) $\Delta H_{S,Z}$ is proportional to the distance from the projected point of S on XY plane to line M_1T_1(i., e. length of line HM_1). If the proportion is given as a constant k, $\Delta H_{S,Z}$ can be represented by

$$\Delta H_{S,Z} = k \times HM_1 = k \times (OM_1 - OH) = k \times (R_M - R_M \cos \Phi_{\mathrm{AB}}) = kR_M(1 - \cos \Phi_{AB}) \tag{1}$$

Similarly, the displacement of point E in Z axial direction $\Delta H_{E,Z}$ can be expressed by

$$\Delta H_{E,Z} = kR_M(1 - \cos \Phi_{CD}) \tag{2}$$

where, Φ_{CD} is the circumferential angle from the slit to line CD. The displacement between points S and E in Z axial direction is $\Delta H_Z = \Delta H_{S,Z} + \Delta H_{E,Z}$.

In general, for an arbitrary angle Φ, considering material continuum of the plate, the distance between points S and E in Z axial direction $H_Z(\Phi) = H_{S,Z}(\Phi) + H_{E,Z}(\Phi)$ can be formulated as

$$H_Z(\Phi) = 2\mathrm{k}R_M \int_0^\Phi (1 - \cos \Phi) d\Phi = 2kR_M(\Phi - \sin \Phi) \tag{3}$$

If the last press has been completed, as shown in Fig.6(b) the distance from point S to point E is equal to pitch p of the finished spiral plate, i. e., $H_Z(2\pi)$=p. It is obvious that $k = p/4\pi R_M$, and

$$H_Z(\Phi) = \frac{p}{2\pi}(\Phi - \sin \Phi) \tag{4}$$

This equation shows the relationship between the distance from point S to point E in Z axial direction and press place in the incremental forming processes.

In each press, the maximum bent angle (before spring back) of the plate is equal to the inclination angle θ of the punches and dies as shown in Fig.7. The displacement of point S in Z axial direction $\Delta H_{S,Z}$ can be expressed by

$$\Delta H_{S,Z} = HM_1 \times \sin\theta \tag{5}$$

From Eqs.(1) and (5), we obtain

$$\sin\theta = k = \frac{p}{4\pi R_M} \tag{6}$$

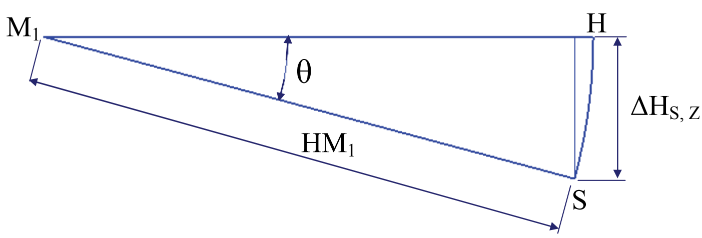


Figure 7: Displacement of point S in Z axial direction

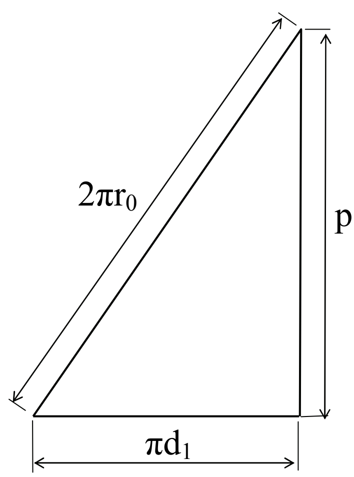


Figure 8: Relationship among d_1, r_0 and p

and

$$p = 4\pi R_M \sin\theta \tag{7}$$

Eq.(7) shows the geometric relation between the pitch of the spiral plate and the inclination angle of the punches and dies. However the spring back (the disk thicknesses and the disk material properties) has not yet obtained.

As shown in Fig.8, the internal diameter of the spiral plate d_1 (diameter of the shaft of screw conveyer) is related to the radius of hole of the flat disk r_0 and the requested spiral pitch p through:

$$d_1 = \sqrt{(2\pi \times r_0)^2 - p^2}/\pi \tag{8}$$

The disk specimen for the incremental press-forming experiment has a hole and a slit as shown in Fig.1(c) and is made of aluminum alloy (A-5052) or steel (SS400) plate. Parameters of the specimens are given as: thicknesses t=1mm, 2mm, 3mm, the external radius of the disk R=50mm, the radius of the hole r_0=25mm, the average radius R_M=37.5mm and the width of the slit is 1mm. As shown in Fig.5, twelve presses are applied on each specimen at twelve places which are labeled from 1 to 12 respectively. Length, thickness and tip radius of the punches and dies are 35mm, 5mm and 2.5mm respectively. Three types of punches and dies with inclination angles θ=±3°, ±4.5°, ±6° are used in the press experiments to investigate the effect of the inclination angle on the spiral pitch and spring back.

3 FEM Analysis

Because the spiral pitch is affected by the thickness and material properties (spring back) of the plate and it can not be predicted precisely, it takes time and material for trial manufacture of the spiral plates. In order to predict damages or cracks on the surface, it is necessary to measure stress and strain during and after pressing. In this research, a three dimensional FEM model of press forming process for the spiral plate based on the experiment is created, and a data processing software for the FEM analysis is developed with Visual C++. Deformation, stress distribution, residual stress and spring back of the spiral plate are analyzed and simulated by FEM software MSC.Marc which is powerful to solve contact problems.

Fig.9 shows the analysis flowchart of twelve press processes for each specimen mentioned above. First, the shapes of specimens, punches and dies used in the experiment are modelled with MSC.Marc. As shown in Fig.10, using functions of solid modelling of MSC.Marc, a disk of external radius 50mm and thickness 1mm (or 2mm, 3mm) is modeled, and a hole of diameter 25mm and a slit of width 1mm are cut from the disk. Punches and dies are treated as rigid bodies as their rigidity in pressing direction is very large. The surface models of two punches and dies of length 35mm, thickness 5mm, inclination angles ±3°(or ±4.5°, ±6°), tip radius

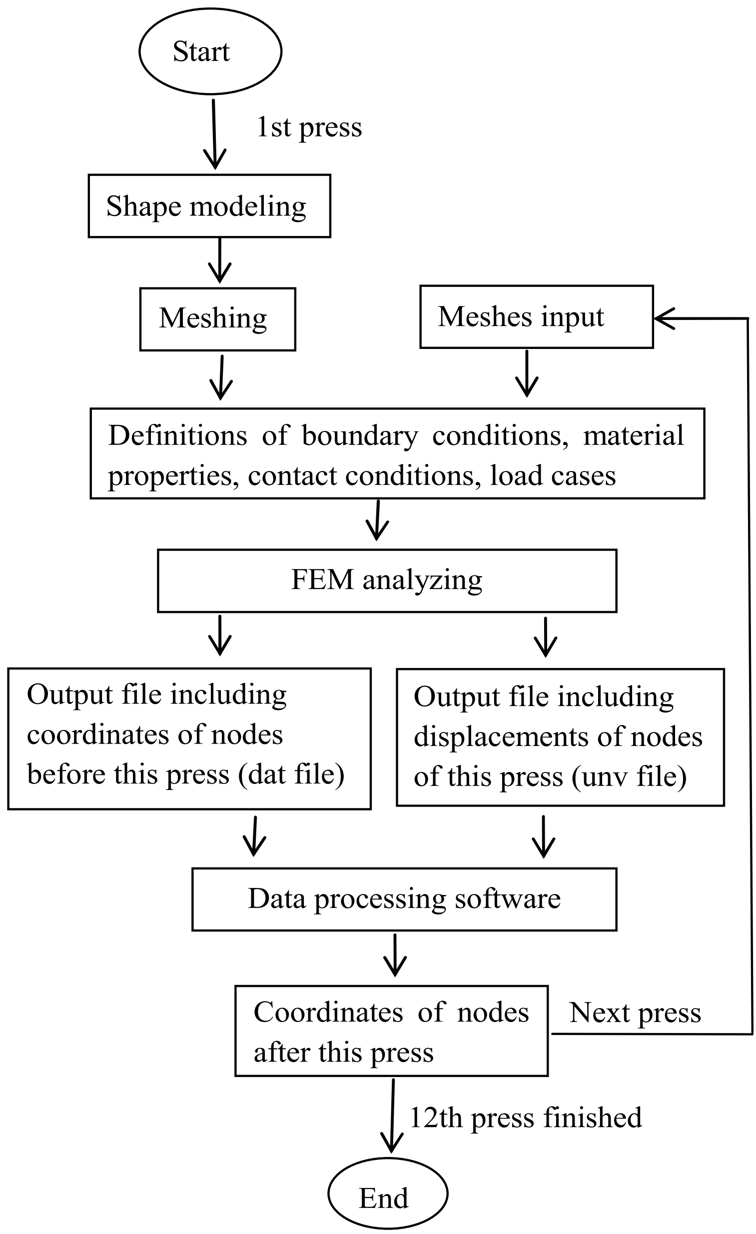


Figure 9: Flowchart of the FEM analysis

2.5mm are also set. Two dies are arranged under the disk at an ang1e of 30° and two punches above the disk are parallel to two dies in the opposite direction.

Next, the disk specimen is meshed as tetrahedral elements. In actual calculations, there are about 28000 meshes and the maximum size of the elements is 1.4mm. As shown in Fig.11, the error of calculated spiral pitch relative that measured in the press experiment is less than 2.15%.

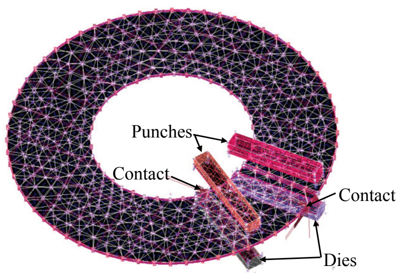


Figure 10: The FEM model

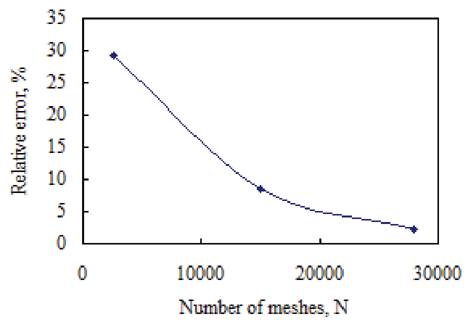


Figure 11: Relationship between the relative error and the number of meshes

Material properties of the specimens are given as follows. (1) Aluminum alloy specimen: Young's modulus 7.5845×10^4MPa, Poisson's ratio 0.3, density 2.7×10^{-6}kg/mm^3, friction coefficient between specimen and punch or die 0.2, flow stress as shown in Tab.1; (2) Steel specimen: Young's modulus 2.0685×10^5MPa, Poisson's ratio 0.3, density 7.8×10^{-6}kg/mm^3, friction coefficient 0.18 and flow stress are shown in Tab.2.

Table 1: Flow stress of aluminum alloy

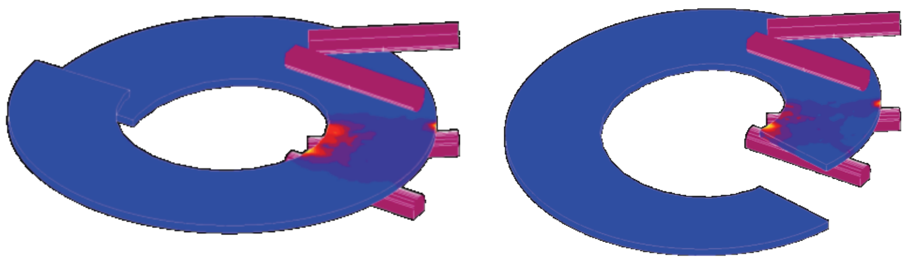
Strain	Stress (MPa)
0	289.59
0.00175	307.36
0.00349	311.36
0.06766	438.97
0.09531	489.2
0.157	560.67
0.207	610.62
0.2623	656.51

Table 2: Flow stress of steel

Strain	Stress (MPa)
0	268.91
0.0007	403.36
0.0016	437.36
0.0026	463.79
0.0033	470.58
0.01	497.47

Initial conditions of the contact between the specimen and two dies are specified by numbers of initial contacted nodes of the specimen. The motion of two punches meets the following requirements: travelling distance=10.5mm, time=0.4s, forward speed=26.3mm/s and back time =0.04s, backward speed=263mm/s.

The coordinates of nodes are obtained from previous coordinates in the "dat" file (the output/input data file for MSC.Marc itself) and current displacements in the "unv" file (output data file for I-DEAS). They are then inputted into MSC.Marc for analysis of the next press repeatedly as shown in Fig.9. Fig.12 shows the results of presses 6 and 12 of a specimen. The finished shape is smooth as that of the press experiment.



(a) Press completed at Position 6 (b) Press completed at Position 12

Figure 12: Results of FEM simulation

4 Results and discussions of the experiment and FEM analysis

4.1 Displacement and spring back at each press

In order to investigate the incremental forming processes, deformation of each press is measured in the experiment and is compared with the value obtained by FEM simulation. Fig.13 shows opening distance H_z between the middle points of two edges of the slit of the disk plate in Z axial direction during each press calculated by FEM, and that measured in the experiment where aluminum alloy specimen (t=2mm) is pressed by punches with inclination angles $\theta=\pm 3^{\circ}$. In the figure, FEM-PRE and FEM-LAST are opening distances before and after spring back calculated by FEM, EXP-PRE and EXP-LAST are the opening distances before and after spring back in the press experiment. Graphs of Eq.(4) are also shown in Fig.13. The values of spring back of each press calculated by FEM, measured in the experiment

(EXP) and calculated by Eq.(4) (where p is replaced with total value of spring back) (EQU) are shown in Fig.14. The calculated results by FEM agree well with those obtained in the experiment or from Eq.(4). Fig.13 and Fig.14 also show that the slopes of the graphs at 1-3 and 10-12 press positions are smaller than those at 5-8, and the slopes at 6 are the maximum. This can be explained by the differential equation of Eq.(4) whose right hand side reaches the maximum at $\Phi = \pi$((6 press position).

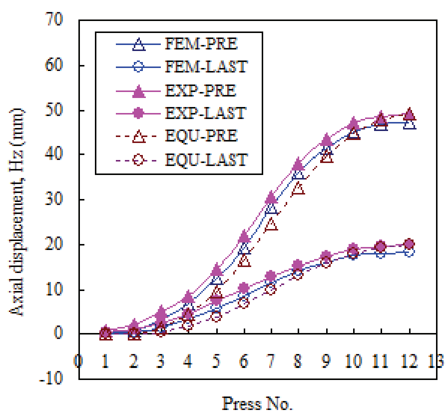


Figure 13: Opening distance before and after spring back at each press position

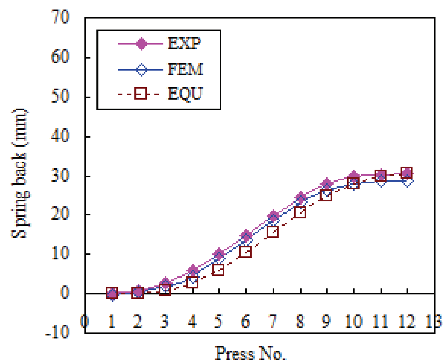


Figure 14: Spring back at each press position

4.2 Axial displacement of the completed spiral plate

In order to assess the shape of the completed spiral plate, axial displacements of the spiral plate along internal, central and external spiral curves (H_i, H_m and H_o) are measured. Fig.15 shows the measured values ($H_{i,exp}$, $H_{m,exp}$ and $H_{o,exp}$). $H_{o,exp}$ is a little smaller than $H_{i,exp}$, because spring back at the outside is a little larger than that at the inside of the spiral plate. Fig.16 shows the values obtained by FEM ($H_{i,FEM}$, $H_{m,FEM}$ and $H_{o,FEM}$) for the same spiral plate. There are small zigzags in the graphs of $H_{i,FEM}$, $H_{m,FEM}$ and $H_{o,FEM}$ due to the small errors in the FEM. The sketches of the experiment and FEM data are almost straight lines and are very close to the desired value (H_d). This means that the height errors in radial direction are very small, the completed spiral surface is very smooth and perpendicular to the axis. As a result, the shape of the spiral plate obtained by the incremental press-forming method is correct and it is predicted well by the FEM simulation.

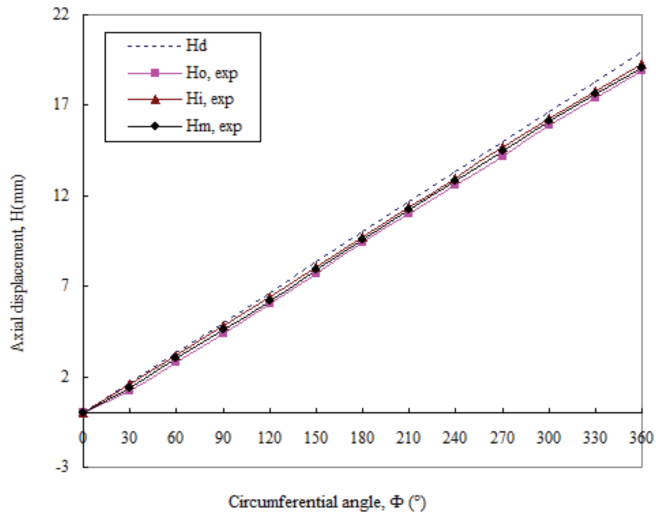


Figure 15: Relationship between circumferential angle (press position) and axial displacement of the spiral plate —experiment

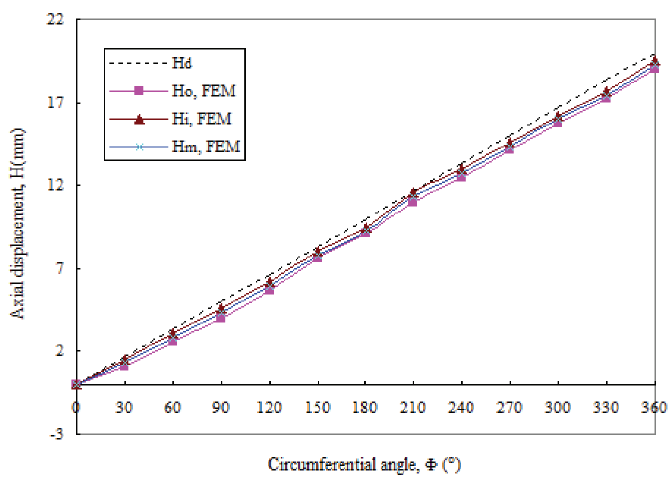


Figure 16: Relationship between circumferential angle (press position) and axial displacement of the spiral plate —FEM simulation

4.3 Relationships of pitch to material and thickness of the spiral plate

Spiral pitches are 15.3mm and 14.9mm as calculated by FEM and measured in the experiment of aluminum alloy specimen (t=1mm) pressed by punches with inclination angles θ=±3°, whereas those of steel specimen are 26.3mm and 25.8mm respectively. The results of FEM agree well with those of the experiment. It is clear that spiral pitch increases with increase in Young's modulus, in contrast to the fact that the spring back decreases with increase in Young's modulus. Because their difference in Young's modulus, the steel specimen plate has a smaller spring back than that of the aluminum alloy specimen. It also has a larger spiral pitch than that of the aluminum alloy specimen.

Relationship between thickness t of aluminum alloy specimen and spiral pitch p pressed by punches with inclination angles θ=±3° is shown in Fig.17. The result of FEM agrees well with that of experiment (EXP). It is clear that the spiral pitch increases and the spring back decreases while the thickness of the plate increases. The reason is that when the plate becomes thicker, plastic deformation near surface of the plate increases and spring back decreases.

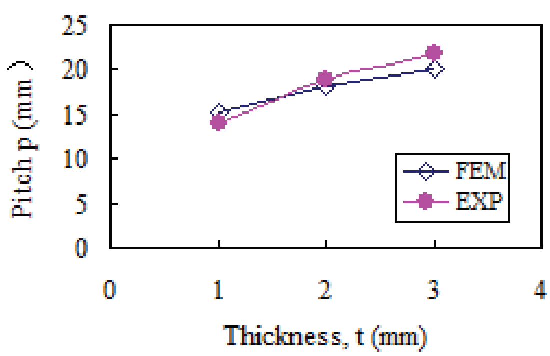


Figure 17: Relationship between thickness of specimen and spiral pitch

4.4 Relationship betwee pitch of the spiral plate and inclination angle of the punch or die

Fig.18 shows the relationship between inclination angle θ of the punch and spiral pitch p of aluminum alloy specimen (t=2mm) obtained by FEM, experiment (EXP) and Eq.(7) (EQU). It shows that the pitch of the spiral plate increases when the inclination angle of the punches and dies increases. The result of FEM matches well with that of experiment. The graph of Eq.(7) has a noticeable difference from those of FEM and experiment. Because influence of spring back on the spiral pitch is not considered in Eq.(7). Eq.(7) can be improved by adding parameters such as thickness and material properties of the plate. Fig.18 also shows that the proportion of spring back to spiral pitch increases while the inclination angle of the punch decreases, and if θ is less than 1° only elastic deformation occurs and spiral shape can not be formed.

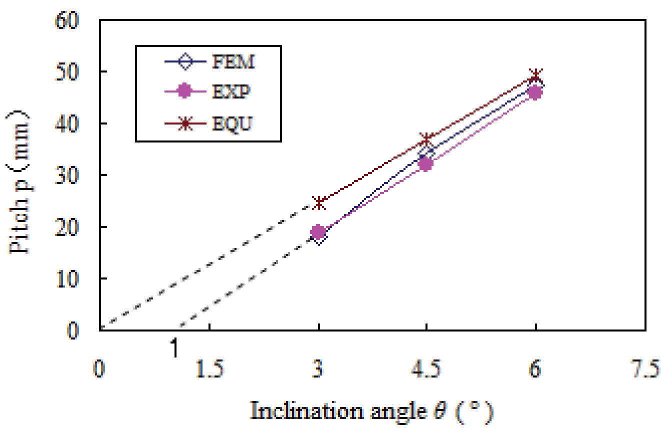


Figure 18: Relationship between inclination angle of the punch and the spiral pitch

4.5 *Stress and strain in the spiral plate*

Stress and strain in the specimen during each press and residual stress and strain after punch back are calculated by FEM. The FEM calculation shows that the equivalent stress during the press forming as well as the residual stress after the spring back reach their maximums at the internal diameter position where the die or punch makes first contact to the disk. Tabs.3 and 4 list the maximum equivalent stress σ_{eq} and strain ε_{eq} as well as maximum equivalent residual stress $\sigma_{R,eq}$ and strain $\varepsilon_{R,eq}$ in aluminum alloy specimen of thicknesses t=1mm, 2mm, 3mm pressed by punch with inclination angles $\theta=\pm 3^{\circ}$, $\pm 4.5^{\circ}$, $\pm 6^{\circ}$, and those in steel specimen with thickness t=1mm pressed by punch with inclination angle $\theta=\pm 3^{\circ}$. It shows that maximum values of σ_{eq}, ε_{eq}, $\sigma_{R,eq}$ and $\varepsilon_{R,eq}$ increase while the thickness decreases, or the inclination angle of the punches and dies increases. With increase in the Young's modulus, maximum values of σ_{eq} and $\sigma_{R,eq}$ increase, but those of ε_{eq} and $\varepsilon_{R,eq}$ decrease. The Maximum value of σ_{eq} of aluminum alloy specimens exceeds their strength limits, and this explains well the damages observed on the specimens. On the other hand, there is no damage observed on steel specimens as its σ_{eq} is within the reasonable range. Stresses and strains will be measured in the experiments in the future.

Table 3: Maximum equivalent stress and strain

Plate material	Aluminum					Steel
θ (°)	3	3	3	4.5	6	3
t (mm)	1	2	3	2	2	1
σ_{eq} (MPa)	411.1	453.4	518.2	506.4	550.1	743.4
ε_{eq}	0.095	0.102	0.116	0.113	0.125	0.037

Table 4: Maximum equivalent residual stress and strain

Plate material	Aluminum					Steel
θ (°)	3	3	3	4.5	6	3
t (mm)	1	2	3	2	2	1
$\sigma_{R,eq}$ (MPa)	374.1	428.9	485	450.8	508.1	684.4
$\varepsilon_{R,eq}$	0.082	0.091	0.097	0.094	0.113	0.029

5 Conclusions

The incremental press-forming method using a pair of V-shaped punches and dies with two opposite inclined edges was developed, and analysis and experiment on the incremental forming process were carried out. The following conclusions can be made from our research: (1) It is possible to form spiral plates of various pitches using the punches and dies with inclination angles. (2) The shape of the spiral plate obtained by the incremental press-forming method is correct and smooth. (3) The FEM model can be used to select appropriate inclination angles of the punches and dies for press operation to save time and cost of trial manufactures. (4) The stress or strain during and after the pressing, as well as the spiral pitch can be calculated by FEM. It is also possible to predict damages or cracks in the spiral plate. (5) The method developed for converting data from I-DEAS to MSC.Marc can be used for solving complicated FEM problems.

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