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Springback Investigation on Sheet Metal Incremental Formed Parts

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***Abstract*—**Incremental forming is a complex forming process with continuously local cumulative deformation taking place during its process, and springback that forming quality affected by would occur. The springback evaluation method based on forming error compensation also was proposed, which it can be defined as the difference between theory and the actual amount of compensation along the measured direction. According to forming error compensation evaluation method, experiments was designed and implemented. And from the results that obtained it can be show, the magnitude of springback average (δE) of formed parts was very small, and the forming precision could be significantly improved by adopting compensation method. Based on double tensile stress state in the main deformation area, a hypothesis that there is little springback be arisen by bending behavior on the formed parts that was proposed.

***Keywords*—**Sheet metal, incremental forming, springback, forming error compensation, geometric accuracy

I. Introduction

INCREMENTAL is an innovative and flexible forming process which belongs to rapid prototyping of sheet metal, with the support of simple die or without it , Also the sheet metal part with higher forming limit and more complex shape can be manufactured using NC machine according to the pre-programmed. Local deformation was taking place as the forming tool moves along the sheet surface, and the finial shape would cumulated by this local deformation. And incremental forming technology is particularly suitable for sheet metal manufacturing during the period of single or small batch production and product trial.

Currently, poor forming quality or poor geometric accuracy & low forming efficiency, especially the geometric accuracy, are the most two important defects that can be hindered the popularization & application of sheet metal incremental forming process. Recently, many scholars concerned with the forming geometric accuracy and its affected factors. The performances of incremental formed parts are typically more than 10 times than industrial requirement for accuracy []. Some studies show that stress relieving is one of the key factor that influenced the geometric accuracy, and forming error can be improve by reducing the residual stress, planning the tooling path, changing the forming process, adopting annealing process [1,2]. Some studies believed that geometric accuracy can be induced by springback, which take place during the process, and compensation methods which can improve the geometric accuracy of the incremental formed parts were suggested. Key factors that influence the springback and its variation laws were analyzed, and springback could be controlled by educing the forming angle [3,4]. Forming accuracy of a set of cone type formed parts was studied by the displacement error method, and results showed that the most important influencing factor is the stiffness of forming tool system [5].In the present work, springback on sheet metal incremental formed part, that forming quality affected by, was investigated. In order study the springback & its value that occurred during the sheet metal incremental forming process, evaluation method based on forming error compensation was proposed by the authors. According to the forming error compensation evaluation method, experiments was designed and implemented. Based on the study result, a hypothesis that there is little springback arisen by bending behavior on the formed parts.

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II. Springback evaluation method

Forming tool which controlled by CNC machine moves along the sheet surface during the Incremental forming process, and local deformation that around the contacting area will be occurred. Continuously local cumulative deformation is taking place as the forming tool moves along the surface and springback that geometric accuracy affected by would occur as the forming tool move away. Different with the bending process, incremental forming is much complex, so how to evaluate the springback is an important question before study it. As shown in Fig. 1., springback evaluation method based on forming error compensation was proposed by the authors, which it can be defined as the difference between theory and the actual amount of compensation along the measured direction. Sprinback value (δ_E) can be calculated by formula (1), and precision of forming error compensation can be calculated by formula (2).

$$\delta_E = \left| \Delta_f - \Delta_t \right| \quad (1)$$

$$\eta_{\delta\Delta} = \frac{\left| \Delta_f - \Delta_t \right|}{\Delta_f} \times 100\% \quad (2)$$

Where δ_E—— Springback value

Δ_f—— Real compensation value

Δ_t—— Analysis compensation value

$\eta_{\Delta\delta}$ —— Compensation accuracy

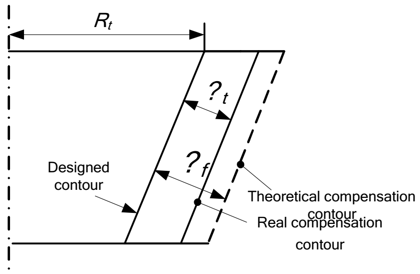

Fig. 1 Springback evaluation method of incremental formed parts

III. Forming Experiments

1) Test Plan

In order to investigate the forming accuracy that influenced by the springback on the formed part that occurred during the incremental forming process, as shown in Fig. 2., a simple conical part was designed by the authors. The forming angle is 50°, the height is 50mm, and the opening radius is 65mm. As soon as the designed model is been built, the part was manufactured by a special NC incremental forming machine. Contour radius on the formed part was measured and compared with the designed model. The difference (Δ_t) between the real size and theoretical one can be take as the compensating value in the coming experiment. And the contour radius of compensating model can be calculated by formula (3).

$$R = R_t + \Delta_t \tag{3}$$

Where R_t —— Radius of theoretical model

R —— Radius of compensating model

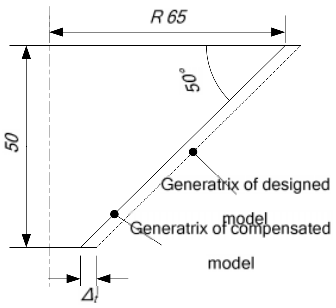

Fig. 2 Designing & compensating model

Fig. 3 NC incremental forming machine

2) Forming experiments

According to the decided test plan, 3D CAD model parts were built adopting CAD/CAM software. NC programs, that incremental forming machine can be droved by, were posted out as soon as the tooling paths were scheduled careful. Table 1 illustrates the forming experimental conditions and process parameters in detail.

TABLE 1
EXPERIMENTAL CONDITIONS AND PROCESS PARAMETERS

Items	Non- compensating	Compensating
Forming machine	Show as Fig. 3	Show as Fig. 3
Tool diameter	Φ 8mm	Φ 8mm
Tool material	HSS	HSS
Tool depth step	0.15~0.3mm	0.15~0.3mm
Tool feed rate	1500~2000mm/min	1500~2000mm/min
Sheet metal	L2Y2	L2Y2
Blank size	160mm×160mm	160mm×160mm
Sheet thickness	0.8mm	0.8mm
lubricant	L--ECC 30	L--ECC 30

In the first step, non-compensating experiment was carried out using the NC incremental forming machine under the conditions & process parameters that were illustrated in Table 1. And the formed part (see Fig. 4.a) was obtained as soon as the experiment finished.

a）Non-compensating part　　b）Compensated part

Fig. 4 Non-compensating & compensated formed parts

In the second step, as illustrated in Fig. 5., the forming tool system could be simplified as a cantilever beam system during the forming process, indeed elastic deformation on the forming tool was taken place under the action of the forces, and then the insufficient forming would be occurred, and the forming precision would be declined. The radial forming force leads to the elastic deformation(x), so the value can be calculated by formula (4), and the analysis compensation (Δ_t) also can be defined as x.

$$x = \frac{Frl^3}{3EI} \tag{4}$$

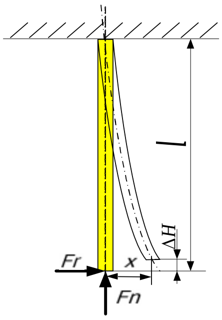

Fig. 5 Deformation scheme of forming tool

Then, based on the above calculation in the second step, compensating CAD model was built with the compensated value of 0.43mm in the coming experiment. The compensating part (see Fig. 4.b) was carried out under the same experiment conditions as before.

Finally, as illustrated in Fig. 6., a series contour layers were built with step of 5mm along the height direction. Outer diameters on the formed parts were measured 10 times at each contour layer, and average was calculated. Differences ($2\Delta_t$) between the experimental diameters and the designed one were determined as soon as the comparisons of measured result were carried out, and all the results were list in

Table and Table .

Fig. 6 Diameter measurements along the contour layers

TABLE II
MEASURED RESULTS & COMPARISONS OF NON-COMPENSATING EXPERIMENT

H	1	2	3	4	5	Average	$2\Delta_t$
5	122.24	122.00	122.24	122.02	122.20	122.14	0.81
10	113.82	113.78	113.84	113.86	113.90	113.84	0.72
15	105.70	105.60	105.42	105.82	105.10	105.53	0.64
20	96.80	97.08	97.34	97.62	97.30	97.23	0.55
25	89.02	89.10	89.02	89.20	89.06	89.08	0.31
30	80.68	80.70	80.80	80.76	80.54	80.70	0.30
35	72.04	72.16	71.98	72.20	72.22	72.12	0.49
40	63.62	64.04	63.70	63.66	63.64	63.73	0.48
45	55.48	55.42	55.26	55.26	55.44	55.37	0.45

TABLE III
MEASURED RESULTS & COMPARISONS OF NON-COMPENSATING EXPERIMENT

H	1	2	3	4	5	Average	2Δt
5	122.72	122.66	122.72	122.68	122.60	122.68	0.28
10	114.42	114.38	114.46	114.38	114.34	114.40	0.16
15	106.08	105.90	105.98	106.00	106.02	106.00	0.17
20	97.72	97.60	97.58	97.62	97.66	97.64	0.14
25	89.58	89.28	89.32	89.30	89.26	89.35	0.04
30	80.98	80.96	80.96	81.00	81.02	80.98	0.01
35	72.48	72.58	72.66	72.42	72.44	72.52	0.09
40	64.24	64.28	64.14	64.12	64.14	64.18	0.03
45	55.78	55.88	55.88	55.70	55.74	55.80	0.03

The actual diameter can be defined by the average value. Under ideal conditions, due to simple fixture and forming parts own restriction, material flow only takes place along the axial direction, and its deformation belongs to slip at plane strain. Based on the plane strain principle, thickness distribution of the formed part can be calculated by cosine rule [6]. Considering the thickness reduction, inner diameter of the formed part can be calculated by formula (9), and the difference between measured diameter and designing one can be represent by formula (10). The measured results & comparisons between Non-compensating and compensating were list in Table .

$$D_f = D_m - 2 \times t_0 \cos\theta \tag{5}$$

$$d\delta = \left| D_f - D \right| \tag{6}$$

Where D_f—— Inner diameter

D_m —— Measurement of outer diameter

$d\delta$ —— Difference of diameter

TABLE IV
COMPARISONS BETWEEN NON- COMPENSATING AND COMPENSATING

H	D_f-non	D_f-compensated	$d\delta$-non	$d\delta$-compensated	Δ_f
5	122.14	122.68	0.81	122.68	0.54
10	113.84	114.40	0.72	114.40	0.56
15	105.53	106.00	0.64	106.00	0.47
20	97.23	97.64	0.55	97.64	0.41
25	89.08	89.35	0.31	89.35	0.27
30	80.70	80.98	0.30	80.98	0.29
35	72.12	72.52	0.49	72.52	0.40
40	63.73	64.18	0.48	64.18	0.45
45	55.37	55.80	0.452	55.80	0.42
Average			0.53	0.11	0.42

IV. EXPERIMENT RESULT ANALYSIS & DISCUSSING

1) Forming process and mechanism analysis

As shown in Fig. 7, sheet metal is fixed on NC incremental forming machine by a simple fixture, and the forming tool can be driven by the pre-programmed NC program. Local cumulative deformation will take place as the forming tool acting on & moving along the sheet surface. This type of local contacting deformation is start from the D point and end of C point.

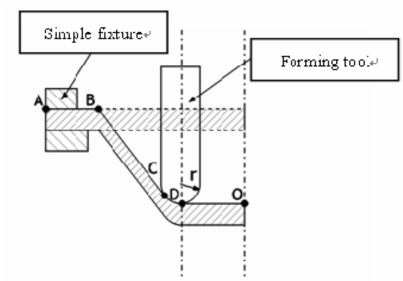

Fig. 7 Sheet metal incremental forming principle

In sheet metal incremental forming process, material deformation mainly takes place in the contacting area (CD coverage). Material will be drawn out along the radial direction, sheet thickness will be reduced, and little changed will be taken place along tangential direction as the forming tool acting on the sheet material during the forming process. The state of stress & strain in the contacting deformation area can be shown as Fig. 8., and the constitutive relationship can be represent by formula (4).

$$\begin{cases}\varepsilon_r = \frac{\bar{\varepsilon}}{\bar{\sigma}}[\sigma_r - \frac{1}{2}(\sigma_t + \sigma_\theta)] \\ \varepsilon_t = \frac{\bar{\varepsilon}}{\bar{\sigma}}[\sigma_t - \frac{1}{2}(\sigma_r + \sigma_\theta)] \\ \varepsilon_\theta = \frac{\bar{\varepsilon}}{\bar{\sigma}}[\sigma_\theta - \frac{1}{2}(\sigma_r + \sigma_t)]\end{cases} \quad (7)$$

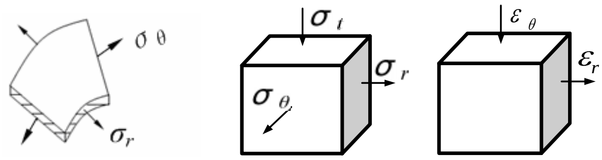

Fig. 8. State of stress & strain in the contacting deformation area

From the yield criterion, it can be shown that

$$\sigma_r - \sigma_t = \beta\sigma_s \quad (8)$$

Plastic deformation causes practically no volume change, so the three plastic strains can be shown that

$$\varepsilon_r + \varepsilon_t + \varepsilon_\theta = 0 \quad (9)$$

Because the radial stress (σ_r) or tangential stress (σ_θ) is much lager than the thickness stress (σ_t), σ_t can be defined as zero. And regarding there is little change of strain along radial direction, the radial strain (ε_θ) also can be defined as zero. Where from formula (4), (5) and (6), solutions were obtained as following

$$\begin{cases}\sigma_r = \beta\sigma_s \\ \sigma_\theta = \beta\sigma_s / 2\end{cases} \quad (10)$$

So the stress state at any points in CD area can be represent by formula (8)

$$\sigma_{ij} = \begin{bmatrix}\beta\sigma_s & 0 & 0 \\ 0 & \frac{\beta\sigma_s}{2} & 0 \\ 0 & 0 & 0\end{bmatrix} = \begin{bmatrix}\frac{\beta\sigma_s}{2} & 0 & 0 \\ 0 & \frac{\beta\sigma_s}{2} & 0 \\ 0 & 0 & \frac{\beta\sigma_s}{2}\end{bmatrix} + \begin{bmatrix}\frac{\beta\sigma_s}{2} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\frac{\beta\sigma_s}{2}\end{bmatrix} \quad (11)$$

During sheet metal incremental forming process, deformation mainly takes place in the contacting area. From formula (8), it can be induced that material at the contacting area is bear dual-tension stress, and the actual state of stress be regarded as a pure deviatoric shear stress superposing a hydrostatic pressure. From the principles of plastic, pure deviatoric shear stress only leads to plastic deformation, and hydrostatic only leads to volume change, it means that plastic deformation is caused by deviatoric stress. Therefore, the material deformation in the contacting area can be taken as a pure shear deformation process. Because there is no bending effect carried out during the deformation process, little springback takes place in the contacting deformation area.

2) Result analysis & discussing

As illustrated in Fig. 9, based on the disposal of measured results, springback values on each contour layers on the formed part and its average have been obtained according to formula (1), and the compensation accuracy on each contour layers on the formed part and its average also have been obtained using formula (2). Form the results of comparison & disposal, it was found that there is little springback take place in the contacting deformation area. And the geometric accuracy can be improved significantly adopting compensating method.

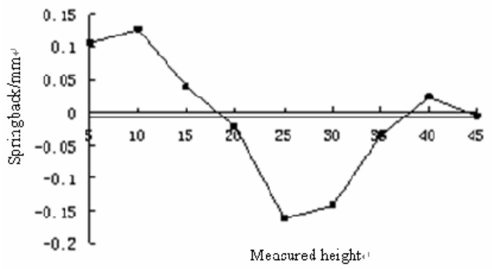

Fig. 9 Curve of springback on the formed part

V. Conclusions

Based on the springback evaluation method that been proposed by the authors, cone type incremental formed parts were studied in the present work. Studies shows that due to no bending effect which leads to little springback take places in the contacting deformation area. And the geometric accuracy of the formed parts can be improved significantly adopting compensating method.

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