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ORIGINAL RESEARCH

The effect of pressing direction on the 5-axis CNC incremental forming quality

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Abstract The effect of pressing direction on forming quality in the 5-axis CNC incremental forming was studied by using the digital simulation technology based on the finite element analysis method. Four kinds of finite element analysis models were created according to the different pressing directions, and were simulated by using ANSYS/LS-DYNA software. Through comparing with the simulation results of the four kinds of finite element analysis models, the relationships between the pressing direction and sheet thickness distribution, sheet thickness thinning rate, outline of the middle surface and the equivalent strain of middle surface were presented.

Keywords Incremental forming · 5-axis CNC incremental forming · Pressing direction · Forming quality

Introduction

The sheet metal CNC incremental forming is a kind of recently developed flexible and dieless forming technology [1]. This technology can directly fabricate sheet pieces from CAD data quickly and economically without any expensive moulds, and can be widely used in the prototyping, multispecies and small batch production, which has wide application prospects in the automobile, shipbuilding and aerospace industry and has been a hot scientific research issue [2].

The basic principle of the CNC incremental forming is that the pressing tool moves on the sheet along the contour of the part according to the pre-programmed tool path and presses the sheet point-by-point so that the sheet is deformed incrementally [3]. So the pressing direction has a great influence on the forming quality.

This paper presents the effect of pressing direction on forming quality through the simulation of CNC incremental forming process under the various pressing directions by using the digital simulation technology based on the finite element analysis.

5-axis CNC incremental forming

CNC incremental sheet metal forming generally adopts 3-axis CNC incremental forming method that presses the sheet from one direction (the pressing direction is always parallel to the z-axis) [4]. In recent years, the research of 5-axis CNC incremental forming that supports multiple directions pressing has been arisen. Obviously, the more larger degrees of freedom pressing tool has, the more complex shape of sheet metal parts could be formed [1]. Different pressing directions bring out different forming effects. The key problem of the multiple directions pressing technology based on the 5-axis CNC incremental forming is to get the best forming effect by pressing the sheet along reasonable pressing direction.

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In 5-axis CNC incremental forming, there are infinite multiple pressing directions for the same pressing point (cutter location point), among them there must exist some reasonable pressing directions that can acquire higher forming quality. The key problem of the study is to find out the effect of pressing direction on forming quality.

In recent years, although there are some researches on CNC incremental forming based on the multi-freedom equipments such as robot [5] and parallel kinematic machine [6], but these researches still adopt the methods of 3-axis CNC incremental forming method (always press the sheet along the z-axis) and have not studied the effect of pressing direction on forming quality and the problems of pressing direction determination.

There are significant differences between 5-axis CNC incremental forming and 5-axis CNC milling in cutter posture determination. The cutter interference and accessibility to workpiece are mainly considered in 5-axis CNC milling. However in the 5-axis CNC incremental forming, not only cutter interference and accessibility to workpiece, but also the effect of cutter posture on forming quality should be considered. Therefore, the method for the determination of the cutter posture in 5-axis CNC milling does not apply to the 5-axis CNC incremental forming. So far, there are no researches reported on the determining of pressing direction for the CNC incremental forming.

Establishing of the finite element analysis model for 5-axis CNC incremental forming

As shown in Fig. 1, 5-axis CNC incremental forming system mainly consists of pressing tool, guidepost, punch, upper and lower pressure plate, bedplate. The upper and lower pressure plate clamps the sheet and can move along the guidepost up and down. The whole system is controlled by 5-axis CNC system to ensure the pressing tool could access the sheet in the different directions so that the sheet can be pressed by multi-directions.

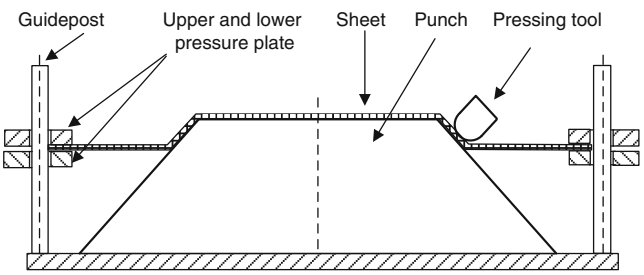

Fig. 1 The 5-axis CNC incremental forming

Because the CNC incremental forming is a complicated nonlinear dynamic loading process, the ANSYS/LS-DYNA software for nonlinear dynamic analysis is used for the simulation. The finite element analysis model of 5-axis CNC incremental forming is established as shown in Fig. 2, which consists of the pressing tool, sheet and punch. In the model, the pressing tool is represented as hemisphere and left out the tool rod part. The shape of the test part is taken as a regular prismoid, whose side length of upper surface and lower surface are 50 and 100 mm respectively, and whose angle between side and bottom surface is 45°. The sheet is a square blank whose edge length and thickness are 150 and 2 mm respectively. Radius of pressing tool is 5 mm.

Material model selection and meshing

The sheet uses the transversely anisotropic material of nonlinear elastoplastic hardened materials model (NO.1010 steel of American standard), and the pressing tool and punch use rigid body material (GCr15 of bearing steel). The parameters of their mechanical property are shown in Table 1. The effective stress–strain curve of transversely anisotropic hardened plastic model is shown in Fig. 3.

The sheet is meshed as Shell163 element and the mapped meshing size of sheet is 1.5 mm. Pressing tool and punch are meshed as Solid164 entity unit of LS-DYNA by using free meshing method and mapped meshing method, and take the full Belytschko-Tsay shell algorithm, which can reasonably explain distortion for sheet metal forming. Figure 4 shows the meshed model.

Contact and constraint

In the CNC incremental forming process, pressing tool always contacts with the sheet and there is dynamical friction between the pressing tool and the sheet, and so there is static friction between sheet and punch. Therefore two kinds of contact are defined: one is the contact between pressing tool and sheet, which is point-surface contact, of which pressing tool and sheet are target and contact respectively, in which static friction coefficient is set for 0.1 and dynamic friction coefficient is set for 0.05. The other is the contact between sheet and punch, which is

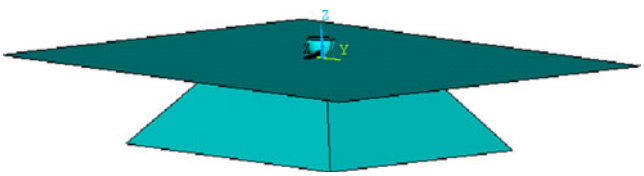

Fig. 2 The finite element analysis model

Table 1 The parameters of mechanical property of the material

	Density/ kg•m^{-3}	Elastic modulus/ Gpa	Poisson's ration	Yield stress/ Mpa	Tangent modulus/ Mpa	Hardening parameter
Sheet	7845	207	0.29	128.5	20.2	1.41
Pressing tool/ punch	7810	212	0.29	–	–	–

surface-surface contact, whose contact and target are sheet and punch respectively, in which static friction coefficient is set for 0.5. The two sets of contact are defined as automatic contact types. In the finite element simulation analysis, this paper takes the way that the each side of the sheet is fastened and the punch moves along the direction of guidepost up, of which the constrain for pressing tool in 5-axis CNC incremental forming is different from that in the 3-axis CNC incremental forming. In 5-axis CNC incremental forming, only the z-axis direction movement of pressing tool and rotation of one axis (mainly depends on the relationship between the initial pressing position of pressing tool and coordinate system) are constrained. Figure 5 shows the finite element analysis model for 5-axis CNC incremental forming after the constraint has been defined.

The description of 5-axis pressing movement in a finite element analysis environment

In the 5-axis CNC incremental forming, the description of pressing movement consists of the description for pressing points and pressing directions. Since the complicated tool path cannot directly be described in ANSYS, first the contour tool path is obtained by using Zhu [7] method and is segmented to be small line segments. Then the extracted x, y, z coordinates of every pressing point and corresponding time t are saved in text files, and are inputted by using array reading function of ANSYS. The loading curve of each pressing point is given in Fig. 6.

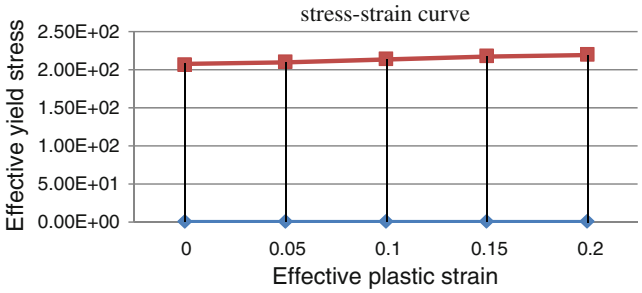

Fig. 3 The stress–strain curve

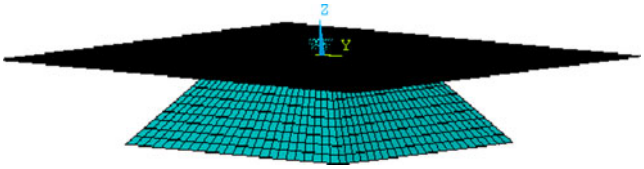

Fig. 4 The meshed model

In the description of pressing direction, angular displacement loading method is used to control the posture of pressing tool. Figure 7 shows the angular controlling loading curve of 45° angle between pressing tool and z-axis (the other angular loading curve can be obtained by changing the y-axis rotating angle).

Digital simulation result and analysis

The simulation for the CNC incremental forming has been done by using ANSYS/LS-DYNA software with the pressing direction angle θ (the angle between pressing direction and z-axis) of 0°, 15°, 30° and 45° under the conditions of material, process and tool path mentioned above.

The effect of pressing direction angle θ on sheet thickness distribution and sheet thickness thinning rate

Figures 8 and 9 show the cloud pictures of sheet thickness distribution and sheet thickness thinning rate that are generated by the simulation with the four pressing direction angles of 0°, 15°, 30° and 45°. The thickness of formed sheet part is mainly in 1.362 to 1.442. When the pressing direction angle is θ=0°, the value of sheet thickness thinning rate is mainly in 27.46% to 31.52%, and the range of sheet thickness thinning is the largest.

With the increase of pressing direction angle, the range of sheet thickness thinning gradually decline. However, when the direction angle is θ=45° (the pressing direction is perpendicular to the sheet), the thickness of sheet is mainly in 1.377 to 1.455 and the sheet thickness thinning rate is mainly in 27.03% to 31.01%, while the range of sheet thickness thinning is the least, and the sheet thickness is more even.

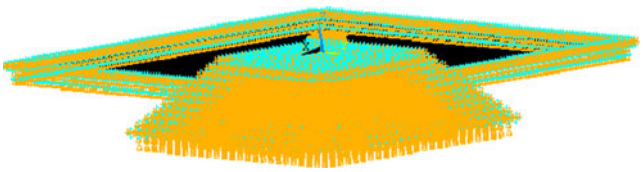

Fig. 5 The constraint model

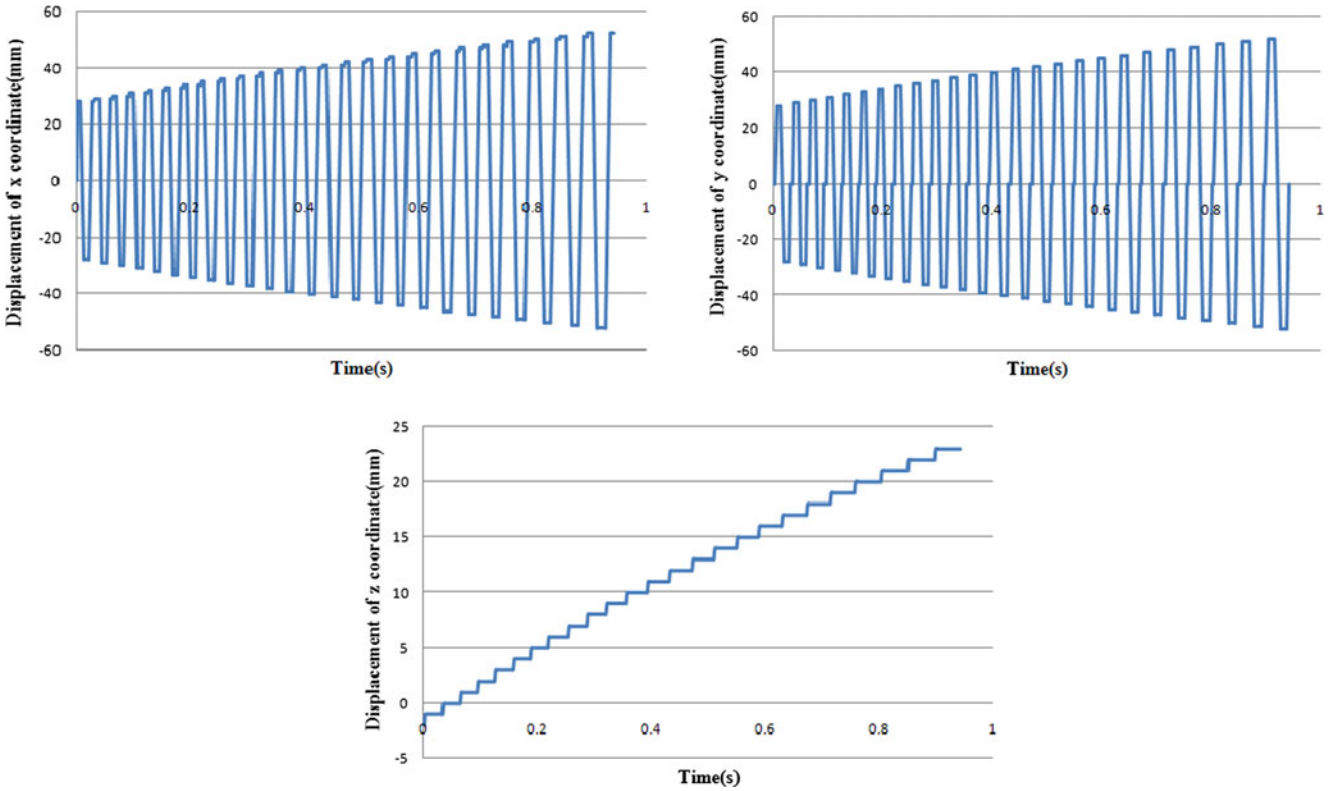

Fig. 6 The displacement loading curves

The effect of pressing direction angle θ on outline of the middle surface

In order to investigate the forming accuracy of the different pressing directions, cut the digital simulation model of each pressing direction using the plane $x=0$ respectively and get the outline of the middle surface using post-processing software LS-PREPOST, then compare the outlines of the middle surfaces of the simulation model, which were generated by four pressing directions, with the outlines of the middle surfaces of the CAD model as shown in Fig. 10. It can be seen from the Fig. 10 that the outline of the middle surface of CAD model is smaller than the outlines of middle surfaces of the simulation models acquired when the pressing direction angles are from 0° to 45°. To more clearly observe the effect of

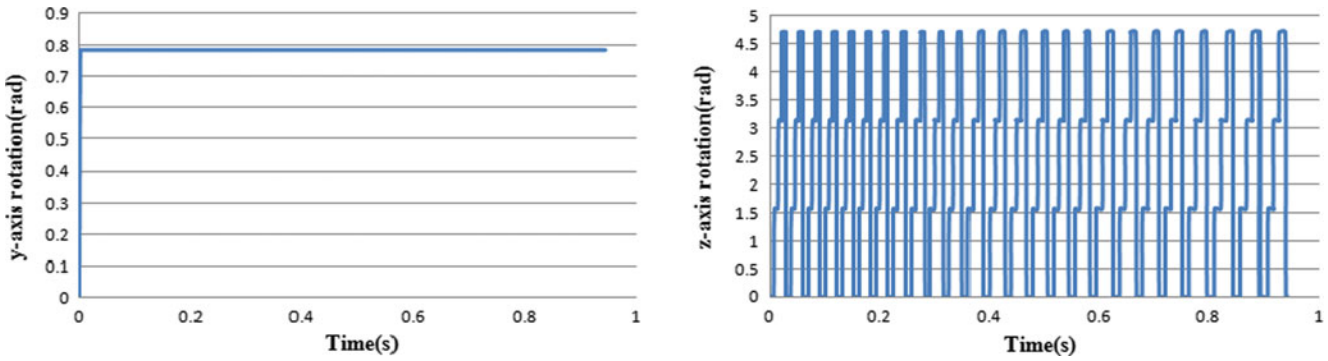

Fig. 7 The angle loading curves of pressing direction angle 45°

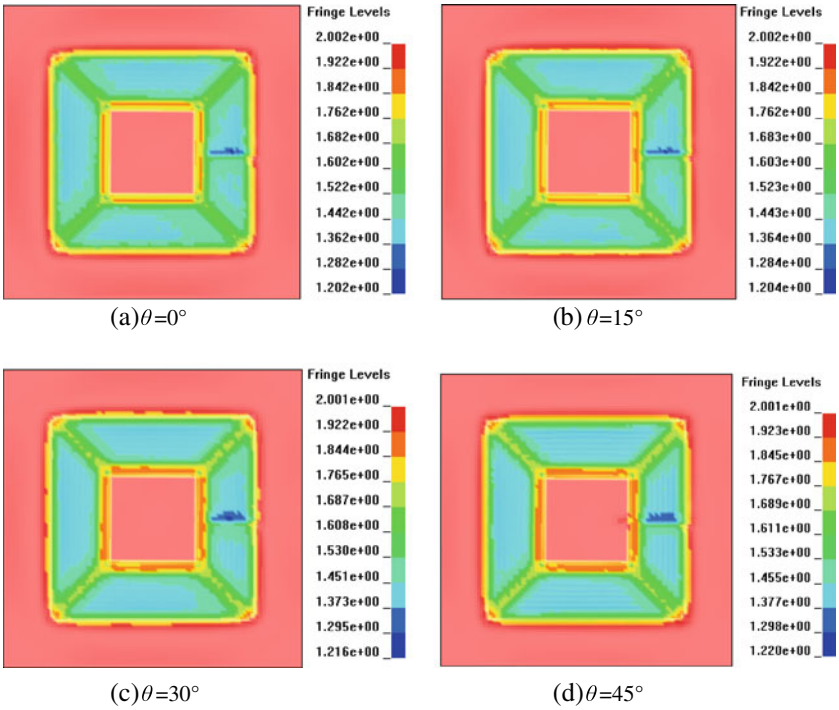

Fig. 8 The cloud picture of sheet thickness distribution

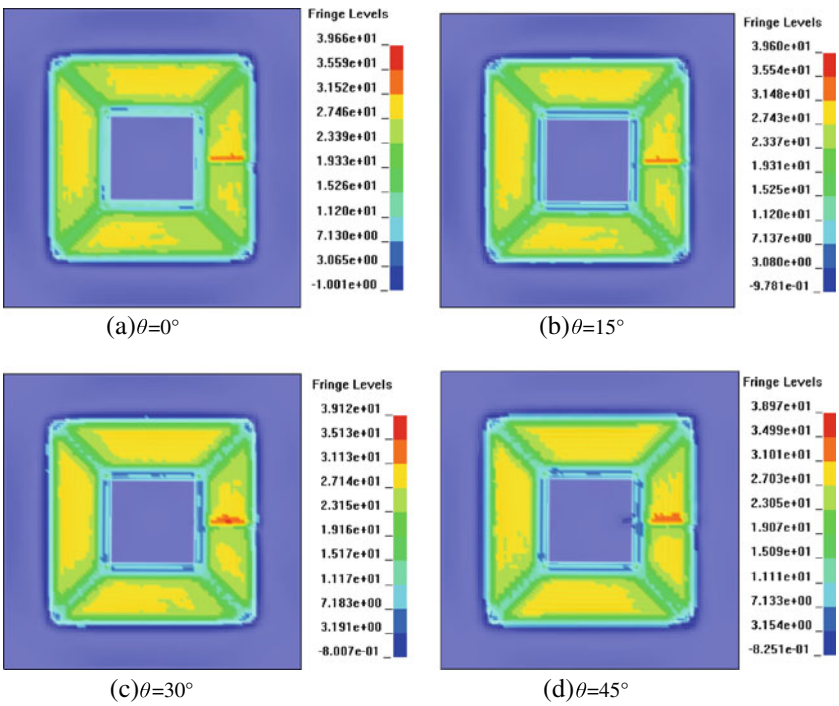

Fig. 9 The cloud picture of sheet thickness thinning rate

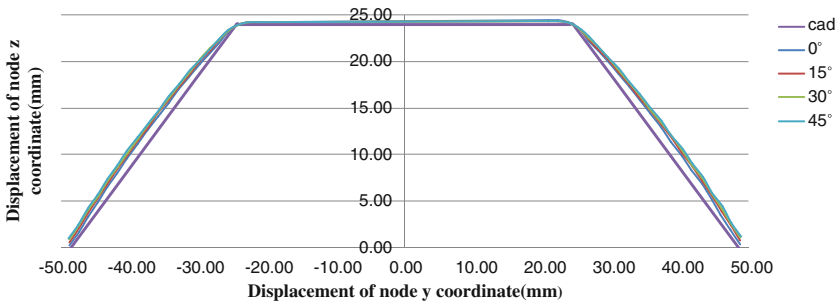

Fig. 10 The outlines of middle surfaces

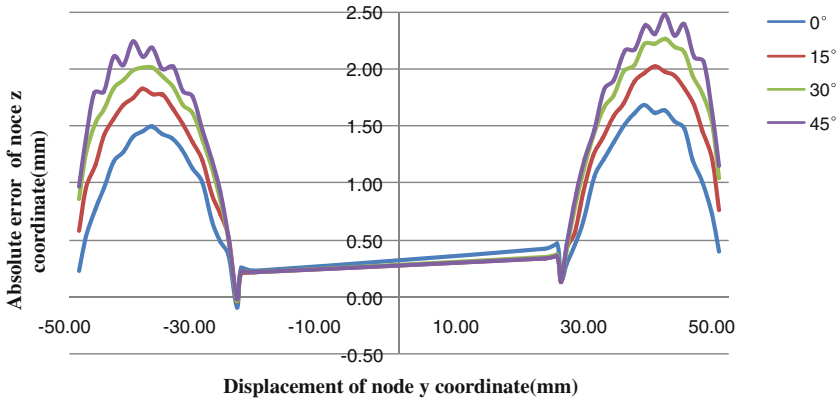

Fig. 11 The absolute errors

pressing direction angle on forming accuracy, as shown in Fig. 11, this paper presents the absolute error curves of outlines of the middle surfaces for every corresponding pressing direction angles. In Fig. 11, the abscissa representatives the y coordinates of selected nodes on the outlines of the middle surfaces, and the ordinate is the algebraic subtraction between the z coordinate of selected nodes on the outline of middle surface of the CAD model and the z coordinate of corresponding nodes on the outlines of middle surfaces of the simulation models generated by the four pressing direction angles. The outline of the middle surface of the pressing direction angle θ=0° is the most close to the outline of the middle surface of CAD model. With the increase of the pressing direction angle, the outline of middle surface more deviates from the outline of CAD model middle surface, the deviation extent is the biggest when θ=45°. The bigger pressing direction angle θ is, the lower forming accuracy is.

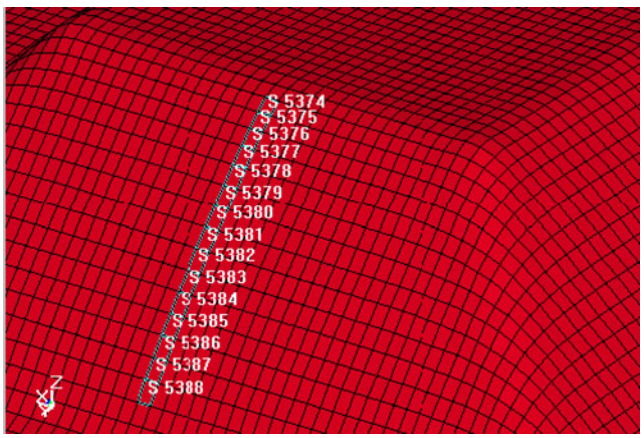

Fig. 12 The simulation model

The effect of pressing direction angle θ on the equivalent strain of middle surface

In order to conveniently observe the effect of the four different pressing direction angles θ on the equivalent strain of middle surface, as shown in the Fig. 12, the elements are selected in middle surface of prismoid, and their middle surface effective strain of four different pressing direction angles are respectively extracted by using LS-PREPOST. As shown as Fig. 13, the middle surface effective strain of pressing direction angle θ=0° is bigger than other three pressing direction angles. With the increase of pressing direction angle, middle surface effective strain of each corresponding element is decrescent before the element 5379 shown in the Fig. 12. However, the effective strain of every angle is almost equivalent after the element 5379. With the increase of

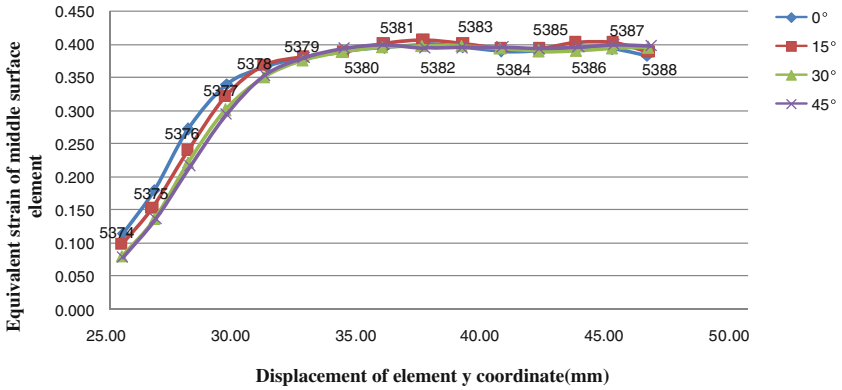

Fig. 13 The equivalent strain of middle surface

pressing direction angle, middle surface effective strain gradually become smaller and will be the smallest when pressing direction is vertical to the surface.

Conclusions

(1) With the increase of pressing direction angle, the sheet thickness thinning range is gradually declining. When the pressing direction is vertical to the surface of the forming part, the sheet thickness thinning range is the smallest.

(2) With the increase of pressing direction angle, the more outline of middle surface of the forming part deviates from the outline of middle surface of CAD model. The range of deviation is the biggest when pressing direction is vertical to the surface of the forming part.

(3) With the increase of pressing direction angle, the equivalent strain of middle surface is gradually diminished. When pressing direction is vertical to the surface of the forming part, the equivalent strain will be the smallest.

(4) The effect of pressing direction on forming quality in the 5-axis CNC incremental forming was studied just by using the digital simulation technology in this paper. While the experimental approach will be presented in the follow-up paper.

References

1. Mo JH, Han F (2008) State of the arts and latest research on incremental sheet NC forming technology. China Mech Eng 19/4:491–497
2. Micari F, Ambrogio G, Filice L (2007) Shape and dimensional accuracy in Single Point Incremental Forming State of the art and future trends. J Mater Process Technol 191:390–395
3. Park JJ, Kim YH (2003) Fundamental studies on the incremental sheet metal forming technique. J Mater Process Technol 140:447–453
4. Jeswiet J, Micari F, Hirt G et al (2005) Asymmetric single point incremental forming of sheet metal. Ann CIRP 54/2:623–649
5. Lamminen L, Tuominen T, Kivivuori S (2005) Incremental sheet forming with an industrial robot. Mater Forum 29:331–335
6. Massimo C, Andrea G, Matteo P (2008) Incremental forming of sheet metal by means of parallel kinematics Machines. J Manuf Sci Eng 130/5:054501.1-054501.5
7. Zhu H, Li JY (2007) Tool path generation for STL model based on vertex offset. J Liaoning Tech Univ 262:273–275