KSME

Springer

Journal of Mechanical Science and Technology 35 (4) 2021

Original Article
DOI 10.1007/s12206-021-0330-9

Keywords:
· Sheet forming
· CNC incremental forming
· Combinatorial optimization of sheet postures
· Thickness uniformity

Correspondence to:
Hu Zhu
zhuhu10@163.com

Citation:
Zhu, H., Wang, Y., Kang, J. (2021). The effect of extrusion direction on the forming quality in CNC incremental forming with multidirectional adjustment of sheet posture. Journal of Mechanical Science and Technology 35 (4) (2021) 1671~1679. http://doi.org/10.1007/s12206-021-0330-9

Received August 8th, 2020
Revised November 26th, 2020
Accepted December 13th, 2020

† Recommended by Editor Hyung Wook Park

The effect of extrusion direction on the forming quality in CNC incremental forming with multidirectional adjustment of sheet posture

Hu Zhu[1], Yang Wang[1] and Jaeguan Kang[2]

[1]College of Mechanical and Electrical Engineering, Shenyang Aerospace University, Shenyang, Liaoning 110136, China, [2]School of Mechanical and Automation Engineering, Kyungnam University, Changwon 51767, Korea

Abstract In the CNC incremental forming, the forming quality will be different with the different extrusion direction. The effects of the different extrusion directions on the forming quality in the CNC incremental forming with the multidirectional adjustment of sheet postures were studied by using three extrusion directions: parallel to the Z-axis, perpendicular to sheet surface and perpendicular to the surface to be formed. The algorithm for calculating the inclination angle of the extrusion tool and determining the extrusion direction vector in the multidirectional adjustment environment of sheet postures was presented. The feasibility of the algorithm was verified by an application example. The equivalent plastic strains under the three extrusion directions were analyzed through the numerical simulation. At the same time, the contour accuracy, thickness reduction and thickness distribution were compared and analyzed through the CNC incremental forming experiment with the multidirectional adjustment of sheet postures under the three extrusion directions.

1. Introduction

As a new technology of dieless forming, the metal sheet CNC incremental forming can be applied to the small batch production, and has been rapidly developed and widely used in recent years [1-4]. However, for the sheet metal parts with the larger forming angles, the problem of excessive thickness reduction or even sheet cracking will occur when the horizontal sheet postures are used in the current CNC incremental forming [5, 6]. With the continuous development of modern society, the demand for complex straight wall parts is increasing. The further development of this technology will be seriously restricted if this problem cannot be solved [7, 8].

In response to the above mentioned problems, some scholars studied a method to solve the problems of uneven thickness distribution and excessive thinning by changing the sheet posture, which achieved some effects. The sheet postures adjustment method is to adjust the horizontal sheet postures to an inclined sheet postures at an angle, thereby reducing the angle between the sheet postures surface and the surface to be formed, that is to reduce the forming angles.

When the curvature of the surface to be formed is different, the horizontal sheet postures needs to be adjusted to different postures to minimize the difference of the forming angles in order to achieve uniform thickness of the formed parts, that is, the sheet postures are changed in multiple directions. The adjustment of the sheet postures is achieved by the extrusion movement of the extrusion tool. The direction and magnitude of the forming force applied to the sheet are different with the different extrusion directions of the extrusion tool, which lead to a big difference of the deformation form and forming effect of the sheet.

The existing CNC incremental forming mostly adopts 3-axis CNC forming method with the extrusion direction parallel to the Z-axis direction. In this way, the influence of the extrusion tool on the forming force, sheet metal deformation behavior and thickness variation was studied [9, 10]. With the increasing demand of sheet metal parts with complex shape, the 5-axis CNC incremental forming technology that can extrude the sheet metal from all directions is gradually emerging [11]. Therefore, it is necessary to explore the influence of extrusion direction on the forming quality.

Zhu and Li [12] studied the influence of the extrusion direction on sheet thickness, profile dimension accuracy and equivalent strain based on the horizontal sheet metal posture in the positive forming by taking 0°, 15°, 30° and 45° as the extrusion direction angle through the numerical simulation method. They found that the forming effect is better when the extrusion direction is perpendicular to the surface to be formed. Considering the extrusion tool as a deformable body, Zhu and Han [13] studied the influence of the extrusion direction on the thickness distribution and forming accuracy in negative forming based on the horizontal sheet metal posture by taking 45°, 60°, 75° and 90° as the extrusion direction angle through the numerical simulation and forming experiment. The results show that when the extrusion direction is perpendicular to the surface to be formed, the thickness distribution is more uniform and the forming accuracy is higher. Although the above mentioned scholars studied the influence of the different extrusion directions on forming quality, they had all studied the influence of the different extrusion directions on the forming quality with the horizontal sheet postures.

Zhu [14], Tanaka [15] and Vanhove [16] studied the method for changing the sheet postures to a certain inclined direction in the forming process so as to obtain the formed parts with more uniform thickness distribution. Zhu and Li [17] divided the formed part containing the straight-walls into the different features, and then gave different sheet postures to the different features to achieve the non-fracture forming of the parts with large forming angle. Zhu and Wang [18] proposed a combination optimization method of multidirectional sheet postures for forming thickness uniformity. Zhu and Liu [19] proposed a method for the forming of straight-wall parts with complex cross section, which multi-directionally change the sheet postures into the inclined surface with small forming angle based on the virtual auxiliary body, so that the straight-wall parts can be successfully formed. Although the above mentioned scholars had adopted the multidirectional sheet postures during the forming process, however, the influence of the extrusion direction on the forming quality in the CNC incremental forming based on the multi-directional sheet metal posture is not discussed.

In the CNC incremental forming of the multidirectional adjustment of sheet postures, there is a problem of the extrusion direction selection for the extrusion tools. The direction and magnitude of the forming force applied to the sheet are different with the different extrusion directions of the extrusion tool, also there is a big difference between the sheet postures transformation effect, sheet deformation and forming effect.

Therefore, the three extrusion directions such as parallel to the Z-axis, perpendicular to the sheet surface, and perpendicular to the surface to be formed were used to study the influence of the different extrusion directions on the forming quality in the CNC incremental forming with the multidirectional adjustment of the sheet postures in the paper.

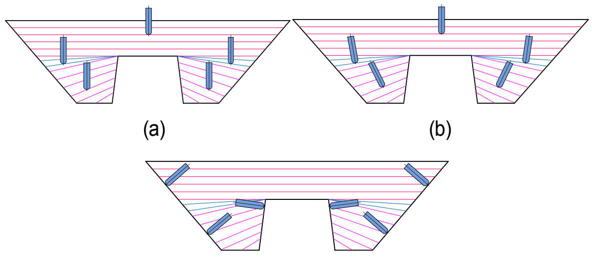


Fig. 1. Extrusion direction: (a) parallel to the Z-axis direction; (b) perpendicular to the sheet surface; (c) perpendicular to the surface to be formed.

2. The different extrusion methods based on the multidirectional sheet postures

The CNC incremental forming based on the multidirectional adjustment of the sheet postures is that the sheet is tilted by the squeezing movement of the extrusion tool during the CNC incremental forming, so as to minimize the forming angle and its difference, and to minimize the thickness reduction and homogenize the thickness. The influence on the forming quality was studied by using the extrusion direction parallel to the Z-axis direction (Fig. 1(a)), the extrusion direction perpendicular to the sheet surface (Fig. 1(b)), and the extrusion direction perpendicular to the surface to be formed (Fig. 1(c)) in the forming with the multidirectional adjustment of sheet postures. And, the calculation method of the direction vector for each extrusion direction was studied.

3. Determination of the posture of extrusion tool

3.1 Calculation of inclination angle of extrusion tool

Compared with the traditional 3-axis CNC machining method, the 5-axis CNC machining method needs not only the spatial coordinates (x, y, z) of the cutter location, but also need two additional rotational freedom to control the extrusion tool postures. The absolute coordinate system of the workpiece is translated to the cutter location point to generate the relative coordinate system that takes the cutter location point as the origin, as shown in Fig. 2.

Among them, $\boldsymbol{v}$ is the extrusion direction vector of the extrusion tool; $\boldsymbol{v}_x$, $\boldsymbol{v}_y$, and $\boldsymbol{v}_z$ are the components of the extrusion direction vector in the X, Y, and Z directions, respectively. The angle α is the angle between the projection of the extrusion direction vector on the YOZ plane and the Z-axis (anteversion angle); the angle β is the angle between the extrusion direction vector and its projection on the YOZ plane (roll angle). The

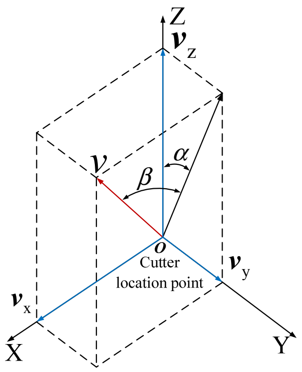


Fig. 2. Determination of the extrusion tool posture.

following formula can be known from the geometric relationship shown in Fig. 2.

$$\begin{cases} \tan\alpha = \dfrac{v_y}{v_z} \\ \tan\beta = \dfrac{v_x}{\sqrt{v_y^2 + v_z^2}} \end{cases}. \tag{1}$$

3.2 Calculation of the extrusion direction vector v

1) Vector ***v*** of extrusion direction parallel to the Z-axis direction. Since the unit normal vector of the Z-axis direction is (0, 0, 1), it is only necessary to assign (0, 0, 1) to the extrusion direction vector at all the cutter location points.

2) Vector ***v*** of extrusion direction perpendicular to the sheet surface. The extrusion direction perpendicular to the sheet metal surface is the normal vector direction of each sheet metal surface. The sheet metal surfaces of all directions can be obtained by constructing the radial lines and triangulating them by using the algorithm of Li [8]. The so-called normal vector direction of the sheet metal surface is the normal vector direction of the triangular surface where the cutter contact point of the extrusion tool head is located. The normal vector $N(x,y,z)$ of a triangular patch can be obtained by using the three vertices $\mathrm{A}(x_a,y_a,z_a)$, $\mathrm{B}(x_b,y_b,z_b)$, and $\mathrm{C}(x_c,y_c,z_c)$ of the triangular patch by the following formula:

$$\mathbf{AB} = (x_b - x_a, y_b - y_a, z_b - z_a) \tag{2}$$

$$\mathbf{AC} = (x_c - x_a, y_c - y_a, z_c - z_a) \tag{3}$$

$$\mathbf{N} = \mathbf{AB}\times\mathbf{AC} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ x_b - x_a & y_b - y_a & z_b - z_a \\ x_c - x_a & y_c - y_a & z_c - z_a \end{vmatrix}. \tag{4}$$

3) Vector ***v*** of extrusion direction perpendicular to the surface to be formed. The normal vector of the inner surface of the sheet metal part to be formed are taken as the vector ***v*** of the extrusion direction.

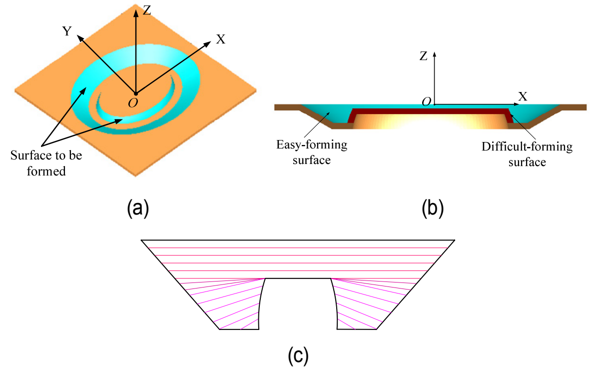


Fig. 3. Verification model: (a) isometric side view; (b) cutaway view; (c) sheet posture.

4. Case studies

The multidirectional adjustment system for sheet posture based on the different extrusion methods was developed using C ++, VC ++ and OpenGL on Windows 7, and the case studies were given as follows by taking the sheet metal part model shown in Fig. 3(a) as example.

Fig. 3(b) shows that the outer surface of the model is a difficult-forming surface with different curvatures. Since the top of the model is easy to form, it is sufficient to directly adopt the horizontal sheet postures during the forming process. When the forming process is conducted to the difficult-forming surface of the nested features inside the model, it is necessary to transform the horizontal sheet postures at different heights to obtain the inclined sheet postures in various orientations to ensure that the forming angles were less than the forming limit angle and the thickness of the formed part were uniform, as shown in Fig. 3(c).

For the model, Figs. 4-6 show the direction vectors of the three extrusion directions such as parallel to the Z-axis, perpendicular to the sheet surface and perpendicular to the surface to be formed. Among them, the blue, black, and green lines L1 represented the extrusion direction vector at the cutter location points on the easy-forming surface; the red and yellow lines L2 represented the extrusion direction vector at the cutter location points on the difficult-forming surface; the green area M represents the surface to be formed, and the purple area N represents the sheet postures in the forming process. Fig. 4 shows the extrusion direction parallel to the Z-axis at the cutter location points on a certain layer during the sheet postures adjustment process.

Fig. 5(a) shows the extrusion direction perpendicular to the sheet surface at the cutter location points on a certain layer when the sheet metal is in the horizontal postures, and the extrusion directions between the cutter locations points are gently transited. Fig. 5(b) show the extrusion direction perpendicular to the sheet surface at the cutter location points on the different sheet postures surface of two layers during the sheet postures adjustment process. It can be seen that when the sheet postures change during the forming process, the extru-

Table 1. Mechanical property parameters.

Name	Density /kg · m^{-3}	Elastic modulus /Gpa	Poisson ratio	Yield stress /Mpa	Tangent modulus /Gpa	Hardening coefficient
Al1060	2700	55.94	0.324	153.6	2.9	0.19775
GCr15	8160	218	0.30	—	—	—
W6Mo5Cr4V2	7810	212	0.29	—	—	—

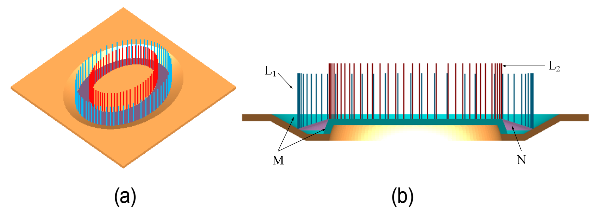


Fig. 4. The extrusion direction parallel to the Z-axis direction: (a) isometric side view; (b) cutaway view.

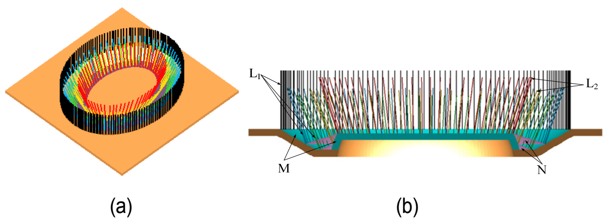


Fig. 5. Extrusion direction perpendicular to the sheet surface: (a) isometric side view; (b) cutaway view.

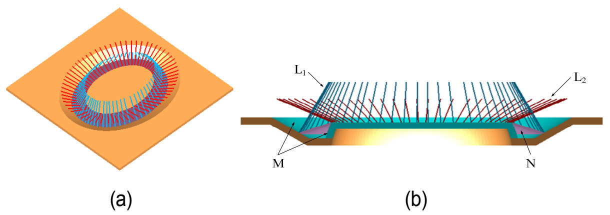


Fig. 6. Extrusion direction perpendicular to the surface to be formed: (a) isometric side view; (b) cutaway view.

sion direction at the cutter location points will also change, but the extrusion directions are always perpendicular to the current sheet surface.

The extrusion directions that are perpendicular to the surface to be formed at the cutter location points on a certain layer in the process of the sheet postures adjustment are shown in Figs. 6(a) and (b) in which the extrusion directions are gently changed at the cutter location points.

5. Finite element numerical simulation

The model shown in Fig. 3 was used as the research object to perform numerical simulations with the extrusion directions respectively parallel to the Z-axis, perpendicular to the sheet surface and perpendicular to the surface to be formed by using the ANSYS/LS-DYNA finite element analysis software, and the analysis of the thickness distribution and equivalent strain of

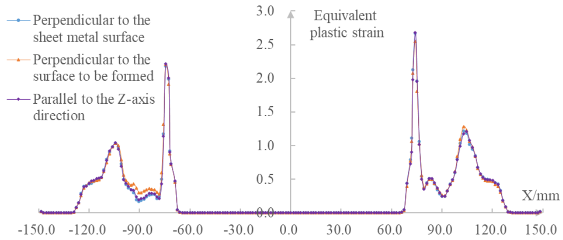


Fig. 7. The equivalent plastic strain curves at $Y = 0$ section.

the sheet material obtained by the simulation were performed by using the LS-Prepost software.

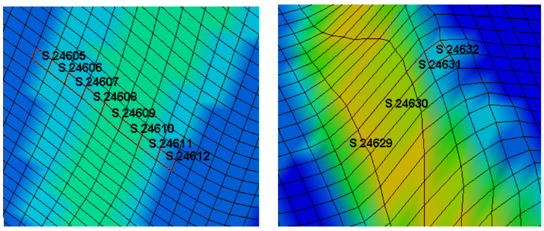
5.1 Parameter setting of the finite element numerical simulation

The finite element numerical simulation model was mainly composed of three parts: the support, sheet and extrusion tool, the material of each part was GCr15, Al1060 and W6Mo5Cr4V2, respectively. The main parameters of each part were set as follows. In terms of the element type selection, the "SOLID 164" 8-node hexahedral element was used for the support; the "SHELL 163" thin shell element was used for the sheet; the "SOLID 164" 8-node hexahedral element was used for the extrusion tool. The "Belytschko-Wong" algorithm in the "SHELL 163" thin shell unit was selected for operation in this paper because the fast operation speed. The support was divided into a tetrahedral free mesh with a size of 4 mm; the sheet was divided into a quadrilateral mapped grid with a size of 1.5 mm; the extrusion tool was divided into tetrahedral free mesh with a size of 1.5 mm. The thickness of the sheet and the radius of the extrusion tool were 0.88 mm and 5 mm, respectively. The mechanical properties of each material are shown in Table 1.

5.2 Analysis of the results of finite element numerical simulation

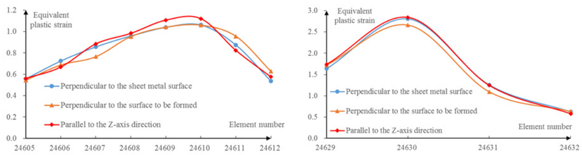
In order to compare the effect of three extrusion directions on the equivalent plastic strain, the equivalent plastic strain on each element at section $Y = 0$ of the model was extracted by using the finite element post-processing software LS-Prepost. Fig. 7 shows the equivalent plastic strain curves.

Fig. 7 shows that the influence trends of three extrusion directions on the equivalent plastic strain of the element on the $Y = 0$ section are approximately the same, and the equivalent plastic strain of the element on the easy-forming surface is



(a) (b)

Fig. 8. Element selection: (a) the element on easy-forming surface; (b) the element on difficult-forming surface.



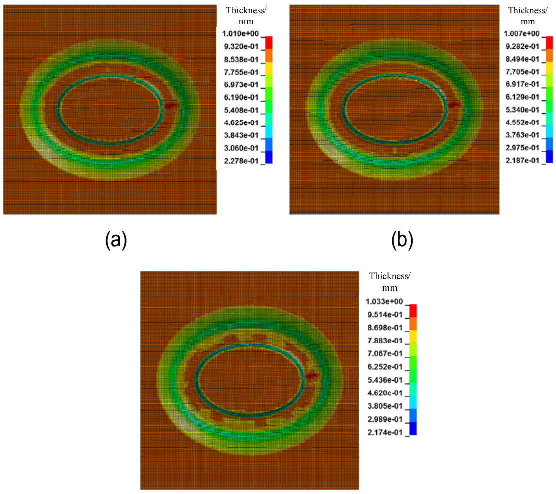
(a) (b)

Fig. 9. Equivalent plastic strain at X = 0 section: (a) easy-forming surface; (b) difficult-forming surface.

smaller than that on the difficult-forming surface which indicates that the degree of the thickness reduction on the easy-forming surface is less than that on the difficult-forming surface.

In order to better compare the equivalent plastic strains of the different extrusion directions, the element of the easy-forming surface and the difficult-forming surface on the X = 0 section were selected respectively as shown in Fig. 8. The element number and the equivalent plastic strain of each element were taken as the abscissa and ordinate, respectively.

Fig. 9(a) shows that the equivalent plastic strain of the elements s24605-s24610 (the depth increases gradually) on the easy forming surface increases with the Z coordinate decreasing (that increases with the depth). When the extrusion direction is parallel to the Z-axis, the equivalent plastic strain of the element is greater than that of other extrusion directions. The equivalent plastic strain decreases with the Z coordinate decreasing (that decreases with the depth increasing) of the elements s24610-s24612 (the depth increases gradually). When the extrusion direction is perpendicular to the sheet surface, the equivalent plastic strain of the element is smaller than that - under the other extrusion direction. The equivalent plastic strains of each extrusion direction near the element S24610 (-80 mm $\le Y \le$ -70 mm and 70 mm $\le Y \le$ 80 mm on the X = 0 section) is the maximum which indicates that the largest deformation and the most serious thinning occurs in the area on the easy-forming surface near this element. That is, the thickness gradually decreases from left to right in the -100 mm $\le Y \le$ -80 mm sections of the easy-forming surface on the left side, and the thickness gradually increases from left to right in the -70 mm $\le Y \le$ -65 mm sections (the thickness of the easy-forming surface on the right side gradually decreases from left to right in 65 mm $\le Y \le$ 70 mm section, and the thickness gradually increases from left to right in 80 mm $\le Y \le$ 100 mm section).



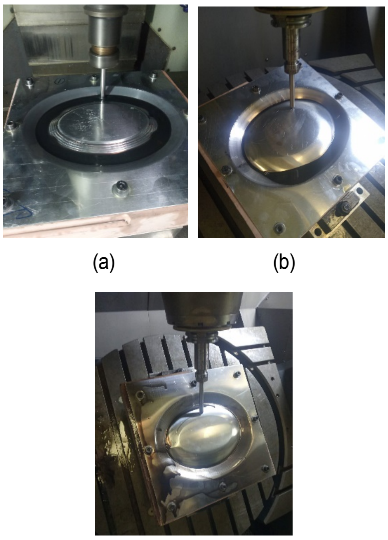
(a) (b)

(c)

Fig. 10. Cloud figure of thickness distribution by the extrusion direction: (a) parallel to the Z-axis; (b) perpendicular to the sheet surface; (c) perpendicular to the surface to be formed.

It can be seen from Fig. 9(b) that the equivalent plastic strain of the elements s24629-s24630 (the depth decreases gradually) on the difficult-forming surface increases with the Z coordinate increasing (that increases with the depth decreasing). When the extrusion direction is perpendicular to the sheet surface, the equivalent plastic strain of the element is smaller than that under other extrusion directions. The equivalent plastic strain of the elements s24630-s24632 (the depth decreases gradually) decreases with the coordinate increasing (that decreases with the depth increasing). When the extrusion direction is perpendicular to the sheet surface, the equivalent plastic strain of the element is greater than that under other extrusion directions. The equivalent plastic strains near the element S24630 (-52 mm $\le Y \le$ -50 mm and 50 mm $\le Y \le$ 52 mm on the X = 0 section) under different extrusion directions all are the maximum, which indicates that the largest deformation and the most serious thinning occurs in the area on the difficult-forming surface near this element. That is, the thickness gradually decreases from left to right in the -53 mm $\le Y \le$ -52 mm sections of the difficult-forming surface on the left side, and the thickness gradually increases from left to right in the -50 mm $\le Y \le$ -46 mm sections (the thickness of the difficult-forming surface on the right side gradually decreases from left to right in 46 mm $\le Y \le$ 50 mm section, and the thickness gradually increases from left to right in 52 mm $\le Y \le$ 53 mm section).

Fig. 10 shows the cloud figure of the thickness distribution obtained by the three extrusion directions. In the Fig. 10, the thickness on the easy-forming surface and the difficult-forming surface of the simulated parts obtained by the three extrusion directions shows a trend of first decreasing and then increasing from left to right, which is consistent with the equivalent plastic strain curve. When the extrusion tool is parallel to the Z-axis, perpendicular to the sheet surface, and perpendicular to the surface to be formed, the minimum thickness of the formed



(a) (b) (c)

Fig. 11. Forming process by the extrusion direction: (a) parallel to the Z-axis; (b) perpendicular to the sheet surface; (c) perpendicular to the surface to be formed.

part is 0.2278 mm, 0.2187 mm, and 0.2174 mm, respectively. That is, the thickness reduction is relatively light when the extrusion tool is parallel to the Z-axis.

6. Forming experiment

The three forming experiments were carried out by using the extrusion tool parallel to the Z-axis, perpendicular to the sheet surface and perpendicular to the surface to be formed and taking the sheet metal part shown in Fig. 3 as the research object. In the forming experiment, the 1060 aluminum sheet with the thickness of 0.88 mm was selected as the sheet material. The forming tool was a hemispherical tool head with a diameter of 10 mm. The lubricant selected in the process was ordinary engine oil. The spindle speed and the feed rate were set to 400 r/min and 600 mm/min, respectively. Fig. 11 shows the forming process of the CNC incremental forming under the three different extrusion directions.

In order to compare the influence of different extrusion directions on the contour accuracy of the formed part, a three-coordinate measuring instrument was used to measure the profile on the $X = 0$ section of the formed part with 2 mm intervals. Fig. 12 shows the profile curve. The normal deviation of the $X = 0$ section profile between the formed part and the theoretical model was evaluated by using the Geomagic studio/ qualify software, as shown in Fig. 13.

From the profile curve and the profile deviation shown in Figs. 12 and 13, it can be seen that when the extrusion direction was parallel to the Z-axis, the profile of each area of the formed part were consistent with the theoretical profile. The bottom of the difficult-forming surface had the largest positive deviation with the value of 1.724 mm, the bottom of the easy-forming surface had the largest negative deviation with the

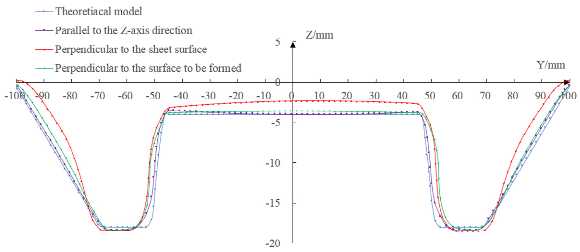


Fig. 12. Profile curve of the $X = 0$ section.

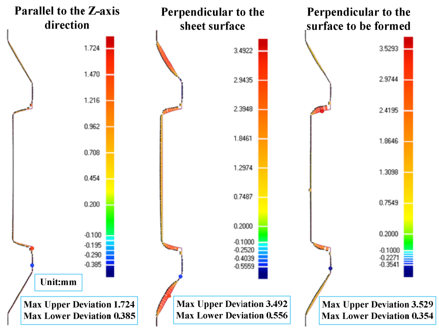


Fig. 13. Normal deviation of the profile.

value of 0.385 mm. When the extrusion direction was perpendicular to the sheet surface, there was a bulging phenomenon in the easy-forming surface area of the formed part and the top of the nested feature. The easy-forming surface had the largest positive deviation with the value of 3.492 mm, and the bottom of the easy-forming surface had the largest negative deviation with the value of 0.556 mm. When the extrusion direction was perpendicular to the surface to be formed, there was a slight bulging phenomenon in the top area of the nested feature of the formed part. Among them, there was the largest positive deviation on the difficult-forming surface with the value of 3.529 mm, and the bottom of the easy-forming surface had the largest negative deviation with the value of 0.354 mm.

Synthesizing the profile curve and the normal deviation of the profile, when the extrusion direction was parallel to the Z-axis, the profile accuracy of the formed part was higher. The reason for the difference in the profile accuracy of the formed parts under the three extrusion directions was shown in Fig. 14.

In Fig. 14, F_1 to F_{12} represents the forces of the extrusion tool that is applied to the sheet metal, and the remaining forces are the component forces in the X and Z directions. From the Fig. 14, when the extrusion direction are perpendicular to the sheet metal, the sheet of the easy-forming surface on the left side is stretched by F_1^1 and F_2^1 superimposed in the same direction, so the bulging will appear on the easy-forming surface (the same for the right side of the sheet). And the nested features are squeezed by F_2^1 and F_3^1, so the top of the nested features will bulge.

When the extrusion direction is perpendicular to the surface to be formed as shown in Fig. 14(b), the sheet of the easy-forming surface on the left side is stretched by F_5^1 and F_6^1 in the opposite direction which can be offset each other, so there

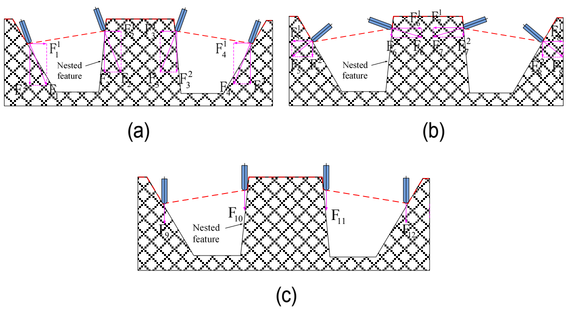


Fig. 14. Sheet force diagram of the extrusion direction: (a) perpendicular to the sheet surface; (b) perpendicular to the surface to be formed; (c) parallel to the Z-axis.

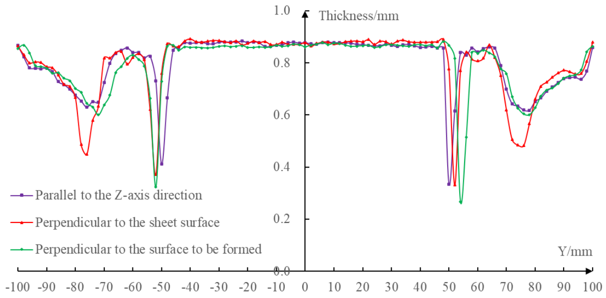


Fig. 15. Curve of the thickness distribution.

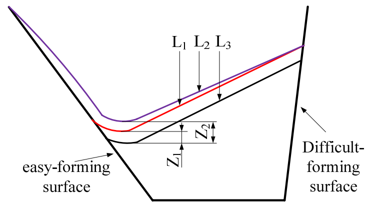


Fig. 16. The sheet posture change.

is no obvious bulging phenomenon (the same for the right side of the sheet); The nested feature is not only subjected to the mutual squeezing action of F_6^1 and F_7^1, but also subjected to the stretching action by F_5^1 and F_8^1 in the opposite direction, which can offset part of the force, so although the top of the nested feature also appeared the bulging phenomenon under this extrusion direction, but the degree was relatively small.

It can be seen from Fig. 14(c) that when the extrusion direction is parallel to the Z-axis, since the direction of the force which the sheet received from the extrusion tool is the vertical direction, the force has no component in the horizontal direction, so the sheet on the easy-forming surface would not be stretched in the horizontal direction, and the top of the nested feature would not be squeezed in the horizontal direction, so there would be no bulging phenomenon, which made the contour accuracy of the formed part under this direction higher.

In order to compare the influence of the different extrusion directions on the thickness distribution of the formed pars, a wire cutting machine was used to cut the formed part along the $X = 0$ section, and the thickness of the cut section was measured with the 2 mm intervals. The thickness distribution curve of the formed parts obtained by the three extrusion directions is shown in Fig. 15.

For the left forming area (-100 mm $\leq Y \leq$ 0 mm), the thickness of the easy-forming surface area (-100 mm $\leq Y \leq$ -65 mm) under the three extrusion directions decreases gradually from left to right between -100 mm $\leq Y \leq$ -80 mm, and increases gradually from left to right between -70 mm $\leq Y \leq$ -65 mm. The thickness of the difficult-forming surface area (-53 mm $\leq Y \leq$ -46 mm) decreases gradually from left to right between -53 mm $\leq Y \leq$ -52 mm, and increases gradually from left to right between -50 mm $\leq Y \leq$ -46 mm. The thickness change rule of the right forming area is the same as the left forming area. This is consistent with the change trend of the equivalent plastic strain curve.

For the left forming area, the thickness of the easy-forming surface under the three extrusion directions all are the minimum in the (-80 mm, -70 mm) range. Among them, when the extrusion direction is respectively parallel to the Z-axis, perpendicular to the surface to be formed, and perpendicular to the sheet surface, the minimum thickness of the easy-forming surface of the formed part under the three extrusion directions is 0.63 mm, 0.6 mm and 0.45 mm, respectively. That is, when the extrusion direction is perpendicular to the sheet surface, the thickness reduction of the easy-forming surface is relatively large. This is due to the bulging phenomenon of the sheet metal existed in the easy-forming surface in this direction, which cause the sheet metal to be deformed to a greater extent and leads to a greater thickness reduction.

In addition, the thickness of the difficult-forming surface under the three extrusion directions all are the minimum in the (-52 mm, -50 mm) range. Among them, when the extrusion direction is, respectively, parallel to the Z-axis, perpendicular to the surface to be formed, and perpendicular to the sheet surface, the minimum thickness of the difficult-forming surface of the formed part under the three extrusion directions is 0.411 mm, 0.371 mm and 0.324 mm, respectively.

Comparing the minimum thickness of the easy-forming surface and the difficult-forming surface under the same extrusion direction, the thickness reduction degree of the easy-forming surface is relatively smaller, and when the extrusion direction is parallel to the Z-axis, the thickness reduction degree of the forming area is smaller, that is, the forming quality of the formed part under this direction is better.

This is because the sheet metal has a certain bulging phenomenon in the extrusion direction perpendicular to the surface to be formed and perpendicular to the sheet surface, which leads to an increase of the forming angles in disguise. When the extrusion direction is parallel to the Z-axis, the forming angles will not be disturbed during the processing because there is no bulging phenomenon, so the forming quality of the formed part under this direction is better. The reason for the difference in the thickness reduction of formed parts under the three extrusion directions is shown in Fig. 16.

When the sheet metal does not bulge and matches the theoretical profile during the forming process, the sheet posture after extrusion by the extrusion tool is L_1. When the sheet has a bulging phenomenon, the sheet posture at the same position is offset from the theoretical contour, and the posture of the sheet is L_2. Since the forming toolpath under the three extrusion directions are the same, only the extrusion directions are different, so when the extrusion tool continues to squeeze, the sheet under each extrusion direction will be squeezed to the same position L_3. At this time, the deformation distance Z_1 experienced by the transition from L_1 to L_3 after the sheet is stretched is shorter than the deformation distance Z_2 experienced by the transition from L_2 to L_3, that is, the degree of deformation is smaller. When the extrusion tool continues to squeeze the sheet to the next layer, the sheet will repeat the deformation mentioned above. Therefore, the deformation degree of the sheet posture with the bulging phenomenon is greater during the forming process, so the thickness reduction is more serious.

7. Conclusion

In the CNC incremental forming with the multidirectional adjustment of the sheet postures, when the extrusion direction is perpendicular to the sheet surface, there is a certain degree of bulging phenomenon at the formed part, the contour accuracy is relatively lowest and the thickness reduction degree is relatively largest. When the extrusion direction is parallel to the Z-axis, the formed part has no bulging phenomenon, the contour accuracy is relatively highest, and the thickness reduction degree is relatively smallest; when the extrusion direction is perpendicular to the surface to be formed, there is a slight bulging phenomenon at the top of the nested feature of the formed part, the contour accuracy and thickness reduction degree are between the other two extrusion directions. The influence under the different extrusion directions on the forming quality in the forming mode with the multidirectional adjustment of the sheet posture was studied in this paper. It is necessary to continue to study the influence under the different sheet postures on the forming quality based on the same extrusion direction in the future.

Conflict of interest

The authors declare that they have no conflict of interest.

Nomenclature

α, β	: The rotation angles of the extrusion tool
$\boldsymbol{v}$	: The direction vector of the extrusion tool
$\boldsymbol{v}_x$	: The components of the extrusion direction vector in the X-axis directions
$\boldsymbol{v}_y$	: The components of the extrusion direction vector in the Y-axis directions
$\boldsymbol{v}_z$	: The components of the extrusion direction vector in the Z-axis directions
$\boldsymbol{N}$	: The normal vector of the triangular patch
$F_i\,(i = 1,2,\cdots,12)$	: The force of the extrusion tool on the sheet metal
L_1, L_2, L_3	: The orientation of the sheet postures
Z_1, Z_2	: The deformation distance of the sheet metal on the Z-axis direction

References

[1] H. Wang, Y. B. Gu, X. Z. Guo, H. T. Wang, J. Tao and Y. Xu, Microstructure and mechanical properties of 2060-T8 Al-Li alloy after warm incremental forming, *J. Mech. Sci. Technol.*, 32 (10) (2018) 4801-4812.

[2] S. Torsakul and N. Kuptasthien, Effects of three parameters on forming force of the single point incremental forming process, *J. Mech. Sci. Technol.*, 33 (6) (2019) 2817-2823.

[3] Y. L. Li, X. X. Chen, Z. B. Liu, J. Sun, F. Li, J. F. Li and G. Q. Zhao, A review on the recent development of incremental sheet-forming process, *Int. J. Adv. Manuf. Technol.*, 92 (5-8) (2017) 2439-2462.

[4] J. R. Duflou, A. M. Habraken, J. Cao, R. Malhotra, M. Bambach, D. Adams, H. Vanhove, A. Mohammadi and J. Jeswiet, Single point incremental forming: state-of-the-art and prospects, *Int. J. Mater. Form.*, 11 (6) (2018) 743-773.

[5] E. Ndip-Agbor, P. Cheng, N. Moser, K. Ehmann and J. Cao, Prediction of rigid body motion in multi-pass single point incremental forming, *J. Mater. Process. Technol.*, 269 (2019) 117-127.

[6] T. T. Cao, B. Lu, D. K. Xu, H. Zhang, J. Chen, H. Long and J. Cao, An efficient method for thickness prediction in multi-pass incremental sheet forming, *Int. J. Adv. Manuf. Technol.*, 77 (1-4) (2015) 469-483.

[7] S. Wu, Y. W. Ma, L. T. Gao, Y. X. Zhao, S. Rashed and N. S. Ma, A novel multi-step strategy of single point incremental forming for high wall angle shape, *J. Manuf. Processes.*, 56 (2020) 697-706.

[8] Z. F. Li, S. H. Lu and P. Chen, Improvement of dimensional accuracy based on multistage single point incremental forming of a straight wall cylinder part, *Int. J. Precis. Eng. Manuf.*, 18 (9) (2017) 1281-1286.

[9] Y. L. Li, X. X. Chen, Z. B. Liu, J. Sun, F. Y. Li, J. F. Li and G. Q. Zhao, A review on the recent development of incremental sheet-forming process, *Inter. J. Adv. Manuf. Technol.*, 92 (5-8) (2017) 2349-2462.

[10] S. Y. Zhao, Y. R. Zhan and C. Zhou, Metal deformation behavior analysis on NC incremental sheet-forming, *Chin. J. Constr. Mach.*, 12 (2) (2014) 140-145.

[11] H. Zhu, H. Y. Wang and Y. B. Liu, Tool path generation for the point-pressing-based 5-axis CNC incremental forming, *Inter. J. Adv. Manuf. Technol.*, 103 (9-12) (2019) 3459-3477.

[12] H. Zhu, N. Li and Z. J. Liu, The effect of pressing direction on the 5-axis CNC incremental forming quality, *Inter. J. Mater. Form.*, 5 (3) (2012) 227-233.

[13] H. Zhu, F. C. Han and Y. B. Liu, The effect of the extrusion direction on the incremental forming quality considering tool

deformation, *Inter. J. Adv. Manuf. Technol.*, 97 (5-8) (2018) 1835-1846.
[14] H. Zhu, J. Ju and J. L. Bai, Sheet thickness homogenization in CNC incremental forming based on tilted forming path, *Comput. Integr. Manuf. Syst.*, 24 (3) (2018) 631-638.
[15] S. Tanaka, K. Hayakawa and T. Nakamura, Incremental sheet forming with direction control of path planes, *Spec. Ed: 10th Int. Conf. Technol. Plast.* (2011) 503-507.
[16] H. Vanhove, J. Gu, H. Sol and J. R. Duflou, Process window extension for incremental forming through optimal work plane rotation, *Spec. Ed: 10th Int. Conf. Technol. Plast.* (2011) 508-512.
[17] H. Zhu and J. L. Li, Research on the CNC incremental forming based on multidirectional real-time adjustment of the sheet posture, *Inter. J. Adv. Manuf. Technol.*, 110 (5) (2020) 1339-1350.
[18] H. Zhu, Y. Wang and J. G. Kang, Research on combinatorial optimization method of multidirectional sheet postures for formed part thickness uniformity, *J. Mech. Sci. Technol.*, 34 (10) (2020) 4251-4261.
[19] H. Zhu and L. T. Liu, Research on the CNC incremental forming of straight-wall parts based on the virtual auxiliary body, *J. Mater. Process. Technol.*, 288 (2021) 116841.

Hu Zhu is a Professor in the College of Mechanical and Electrical Engineering at Shenyang Aerospace University. He received his B.S. from Jilin University, and M.S. and Ph.D. in the Department of Mechanical Design and Production Engineering at Seoul National University. His current research interests include CAD/CAM, 3D printing, CNC incremental forming.

Yang Wang is currently a M.S. Student in the College of Mechanical and Electrical Engineering at Shenyang Aerospace University. He received his B.S. from the Mechanical Manufacturing and Automation at Shenyang Aerospace University. His research interests include CAD/CAM, CNC incremental forming.

Jaeguan Kang is currently a Professor in the Division of Mechanical Engineering at the Kyungnam University. He received his Ph.D. from Pohang University of Science and Technology, M.S. from Korea Advanced Institute of Science and Technology, B.S. from Seoul National University. His primary research interests include CAD/CAM, Incremental sheet metal forming.