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ORIGINAL ARTICLE

Research on the CNC incremental forming based on the unequal feed speed

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Abstract

Aiming at the problems of the CNC incremental forming based on the constant feed speed, an algorithm for the unequal feed speed determining that is adaptive to the surface features and a method for the CNC incremental forming based on the unequal feed speed were proposed. The volume change rate threshold was calculated based on the volume average change rate of the sheet metal involved in the forming and the volume change rate between two adjacent path points. And then, the feed speed between the adjacent path points was determined by the threshold value. Thus, for the sheet metal parts with the complex shape, the different feed speeds were assigned to the regions with different forming angles according to the shape features of the sheet metal parts so that the formability and the forming quality were improved under the same forming efficiency. At the same time, the finite element analysis method for the CNC incremental forming based on the unequal feed speed was given out by calculating the time node points of the forming tool head at each path point, according to the distance between the two adjacent path points and the determined feed speed. The numerical simulation analysis and the forming experimental results show that the CNC incremental forming based on the unequal feed speed is better than the CNC incremental forming based on the constant feed speed, which can improve the profile accuracy of the sheet metal parts, the surface roughness, and formability that under the same forming efficiency.

Keywords CNC incremental forming · Unequal feed speed · Formability · Profile accuracy

1 Introduction

The CNC incremental forming technology is a new sheet metal forming technology. The principle of the technology is that the extrusion tool head moves along the pre-programmed forming path under the control of the CNC machine tools and extrudes the sheet metal point by point so as to make the sheet metal occur the plastic deformation, which are accumulated into the complex shape sheet parts incrementally [1].

Due to its high flexibility, low cost, low environmental pollution, and high formability, it has great economic value in the production of the small batch sheet parts such as aviation, medicine, and new product development, which has attracted the attention of the majority scholars [2]. The forming quality and forming efficiency of the sheet parts are still the main reasons that restrict the development of the CNC incremental forming technology. The feed speed not only affects the forming efficiency of the sheet parts but also has an important influence on the forming quality of the sheet parts. Raju [3] studied the forming process parameters using gray correlation analysis and surface response method. Their results showed that the feed speed is the most influential process parameters on the forming quality of the sheet parts. Therefore, so far, many scholars have studied the feed speed in the CNC incremental forming: Bastos [4] and Hamilton [5] found in the studies of the feed speed that the surface roughness of the sheet parts increases with the increasing of the feed speed. Gulati [6], Le [7], and Hama [8] had found through the researches of the process parameters, that the maximum forming angle of the sheet parts to be formed increases with the decreasing of the feed speed, the formability of the sheet parts decreases with the increasing of the feed speed.

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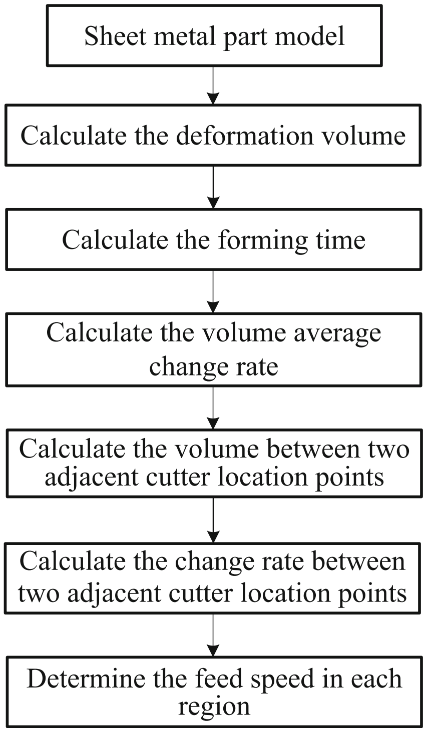


Fig. 1 Algorithm flow

Bagudanch [9] obtained using the orthogonal test method that the smaller the feed speed, the smaller and more uniformity the engineering stress of the extrusion tool head and the sheet parts.

At present, the constant feed speed is used in the CNC incremental forming process. However, the following drawbacks exist when using a constant feed speed: (1) If the feed speed is large, the formed sheet parts will have the poor surface quality, low formability, and low profile accuracy; (2) On the contrary, if the feed speed is small, the forming quality of the sheet parts will be improved, but the forming efficiency is low and the processing cost is high. McAnulty [10] had found through the investigation that the high forming efficiency and

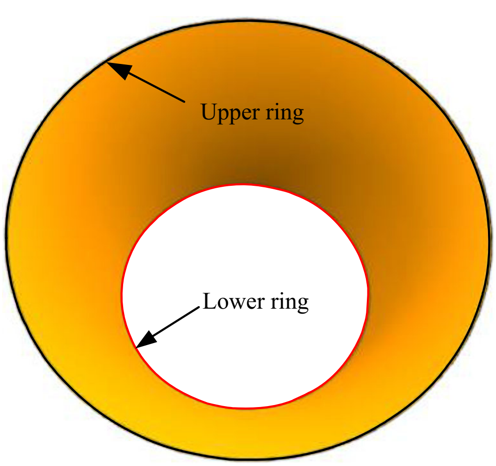


Fig. 2 Edge rings of the internal surface

formability can be achieved by optimizing the feed speed, but McAnulty did not give the optimization method of the feed speed.

In this paper, aiming at the existing problems of the CNC incremental forming method based on the constant feed speed, an unequal feed speed determination algorithm to adapt to the complex shape sheet parts and a CNC incremental forming method based on the unequal feed speed are proposed.

2 The unequal feed speed determination

2.1 Overall method

In the CNC incremental forming, the smaller the feed speed is, the slower the plastic deformation of the sheet metal is, the higher the formability and the profile accuracy are. But the forming efficiency is low and the forming costs are high. When the feed speed is large, although it can improve the forming efficiency and reduce the forming cost, the material flow speed is fast, the plastic deformation is insufficient and the stress concentration is easy to occur, and the formability and contour accuracy of the sheet metal are reduced.

In order to meet the forming quality requirements of the different shape sheet parts, a method for the feed speed determination based on the material change rate was proposed. That is, in the large forming angle region where the sheet metal thinning rate is large, because the sheet metal involved in deformation is less and the sheet parts are easy to be broken, the lower feed speed is adopted. The formability of the sheet parts can be improved by reducing the stress and stress concentration phenomenon that the extrusion tool head applied on the sheet metal. In the region with small forming angle, due to the small thickness thinning rate, the large feed speed should be adopted to increase the sheet parts forming efficiency.

In this paper, an algorithm for the determination of the unequal feed speed and the method for the CNC incremental forming based on the unequal feed speed are proposed, which can meet the requirements of the forming quality and improve the forming efficiency of the sheet parts.

2.2 Unequal feed speed determination algorithm

Firstly, the volume change rate threshold [11] was determined based on the volume average change rate and the actual change rate of the sheet metal that involve in the forming, according to the surface characteristics of the sheet part to be formed. Then, the feed speed is determined according to the volume change rate threshold.

Therefore, for the complex shape sheet parts, the different feed speeds can be determined for the different forming angles region based on the shape characteristics of the sheet parts to be formed. The algorithm flow is as shown in Fig. 1.

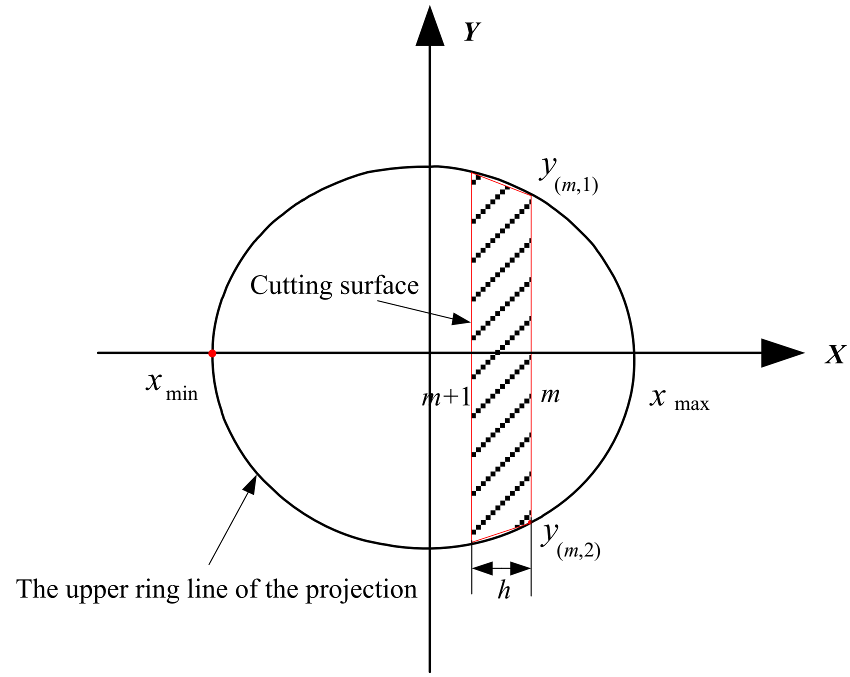


Fig. 3 Cutting the edge ring line of the projection

(1) Calculate the volume of the sheet metal that is involved in the deformation during the forming process.

1). Extract the upper edge ring of the inner surface of the part to be formed [12], the upper and lower edge rings are shown in Fig. 2.

2). The upper edge ring is projected onto the *xoy* coordinate plane. The *z*-coordinate value of each point of the upper edge ring is replaced with 0, then the points on the upper edge ring are transformed into the points that projected onto the *xoy* plane. Remove the duplicated points on the *xoy* plane and follow the clockwise direction to sort the points. Find out the maximum value $x_{\max}$ and minimum value $x_{\min}$ in the *x*-axis direction, and then sequentially connect the projected coordinate points based on the adjacent relationship.

3). Calculate the sheet metal volume *V* located in the upper edge ring. The projection lines of the upper ring was cut by using the vertical plane which is perpendicular to the *x*-axis with a distance *h* (*h* is the distance between the cutting planes) from the maximum value $x_{\max}$ along the *x*-axis direction, as shown in Fig. 3. The *y*-coordinate values $y_{m,1}$ and $y_{m,2}$ of the intersection points of the cutting plane and the projection of the upper edge ring are calculated, the distance l_m ($m = 0, 1, 2\cdots$) between the two intersection points is calculated according to Eq. (1). The distance *l* between the two intersection points of the cutting plane and the projection of the upper edge ring is obtained in order. The volume V_m between two adjacent cutting planes in the upper edge ring is calculated according to the Eq. (2), and t_0 is the original thickness of the sheet metal. The sheet metal

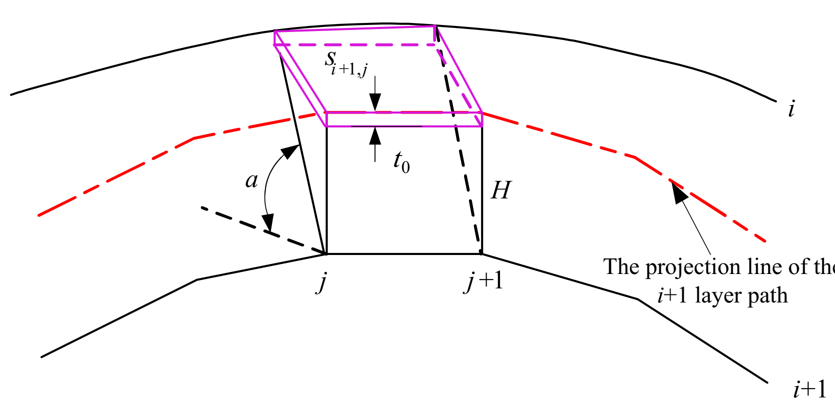


Fig. 4 Contour line projection

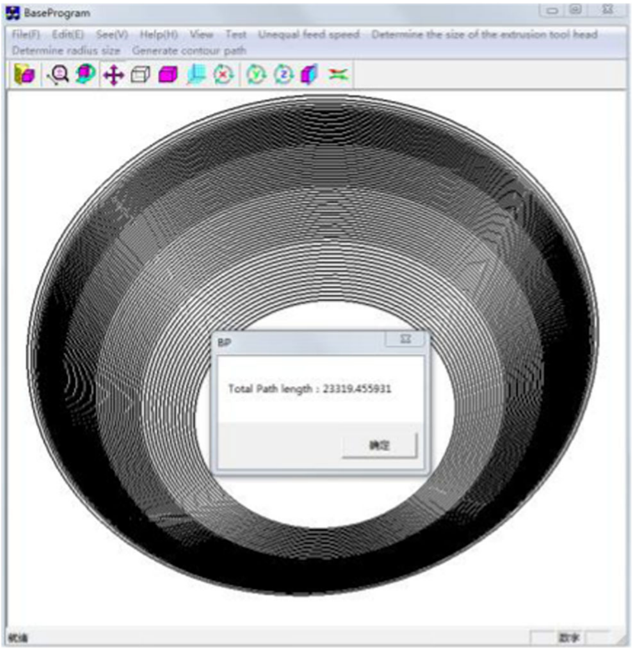


Fig. 5 User interface

volume V in the upper edge ring is calculated using Eq. (3) according to the principle of calculus.

$$l_m = \left| y_{m,1} - y_{m,2} \right| \tag{1}$$

$$V_m = \frac{l_m + l_{m+1}}{2} \cdot h \cdot t_0 \tag{2}$$

$$V = V_1 + V_2 + \cdots V_m + \cdots + V_n \tag{3}$$

4). Calculate the volume v of the sheet metal in the lower edge ring. Extract the lower edge ring of the inner surface of the model to be formed, then execute step 2) and step 3), and calculate the volume v of the sheet metal in the lower edge ring (if the model to be formed is hemispherical, then $v = 0$). Calculate the sheet metal volume ΔV involved in forming according to Eq. (4).

Table 1 Feed speed of model 1

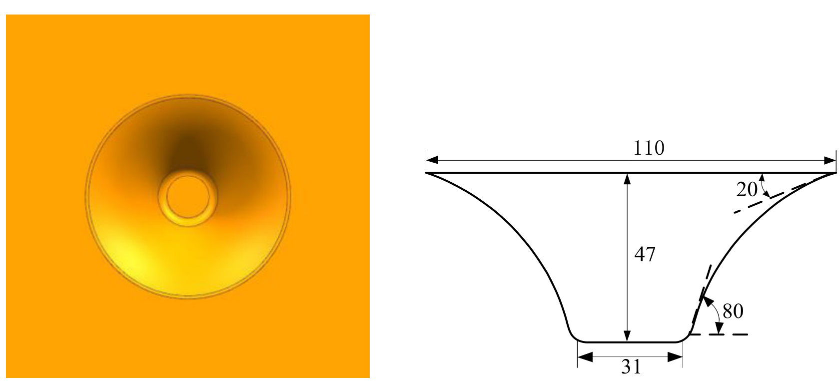
Model depth (mm)	Forming angle (°)	Feed speed (mm $\min^{-1}$)
0~23	20~55.5	4000
23~47	55.5~80	1000

$$\Delta V = \left| V - v \right| \tag{4}$$

(2) Calculate the total length L of the forming path. Cutting the cutter location surface of the model using the horizontal plane with a certain layer distance to generate the cutter location points, and then the cutter location points were conducted the operation of the removing duplicated, sorting, and numbering. The distance $L_{i,j}$ between two adjacent cutter location points was calculated in turn according to the Eq. (5) (i is the number of the layers of the contour path where the cutter location point is located, $i = 0, 1, 2, \cdots$; j is the number of the cutter location points on the each contour line, $j = 0, 1, 2, \cdots$). The total length L of the forming path was obtained by accumulating the distances between the adjacent two cutter location points.

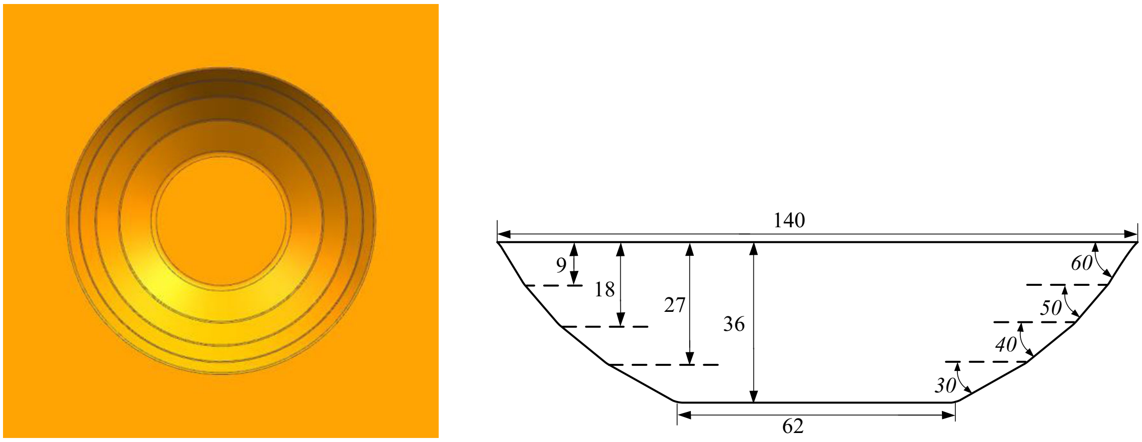
$$L_{i,j} = \sqrt{\left(x_{i,j} - x_{i,j+1}\right)^2 + \left(y_{i,j} - y_{i,j+1}\right)^2} \tag{5}$$

(3) Calculate the forming time T. According to the feed speed F_0 set by the experience, the required forming time T is calculated based on the Eq. (6) when the sheet part is formed with the empirical feed speed F_0.



(a) (b)

Fig. 6 Model 1. **a** Top view. **b** Profile size



(a) (b)

Fig. 7 Model 2. **a** Top view. **b** Profile size

$$T = \frac{L}{F_0} \tag{6}$$

Calculate the volume average change rate v of the sheet metal involved in the forming. The volume average change rate Δv of the sheet metal can be calculated according to the Eq. (7).

$$\Delta v = \frac{\Delta V}{T} \tag{7}$$

On the same contour line, calculate the sheet metal volume $V_{i+1,\,j}$ that is involved in the forming when the extrusion tool head moves between the two adjacent cutter location points. As shown in Fig. 4, the coordinates of the point $P^*_{i+1,j}$ are $(x^*_{i+1,j}, y^*_{i+1,j}, z^*_{i+1})$ and the coordinates of the point $P^*_{i+1,j+1}$ are $(x^*_{i+1,j+1}, y^*_{i+1,j+1}, z^*_{i+1})$, where $P^*_{i+1,j}$ is the cutter contact point corresponding to the cutter location point $P_{i+1,\,j+1}$, $P^*_{i+1,j+1}$ is the cutter contact point corresponding to the cutter location point $P_{i+1,\,j+1}$, and α is the forming angle of the triangular facets between the cutter contact points $P^*_{i+1,j}$ and $P^*_{i+1,j+1}$. H is the layer distance; $L^*_{i+1,j}$ is the distance between the adjacent two cutter contact points $P^*_{i+1,j}$ and $P^*_{i+1,j+1}$. $s_{i+1,\,j}$ is the sheet metal area that is involved in the forming when the extrusion tool head moves between the cutter location point $P_{i+1,\,j}$ and $P_{i+1,\,j+1}$, which can be obtained by Eq. (8). The forming sheet metal volume $V_{i+1,\,j}$ that is involved in the forming when the extrusion tool head moves between the cutter location points $P_{i+1,\,j}$ and $P_{i+1,\,j+1}$ on the $i+1$ contour line was obtained according to Eq. (9).

$$s_{i+1,j} = L^*_{i+1,j} \cdot \frac{H}{\tan\alpha} \tag{8}$$

$$V_{i+1,j} = s_{i+1,j} \cdot t_0 \tag{9}$$

Calculate the change rate $v^*_{i+1,\,j}$ of the sheet metal volume between two adjacent cutter location points. The movement time $T_{i+1,j}$ of the extrusion tool head between two adjacent points on the path is calculated according to Eq. (10) when the forming is performed at the feed speed F_0. Then, the sheet metal volume change rate $v^*_{i+1,\,j}$ between two adjacent points on the path in the forming at the feed speed F_0 can be calculated from Eq. (7).

$$T_{i+1,j} = \frac{L_{i+1,j}}{F_0} \tag{10}$$

Determine the feed speed in each region of the sheet parts. The threshold value n_j of the extruded sheet volume change rate can be calculated according to Eq. (11) and the threshold value is modular processed (when $n_j > 0.8$, $n = 2$; if $n_j \leq 0.8$, $n = 0.5$). The modular value can be made appropriate adjustments according to the specific model considering the forming environments by user). The feed speed F within the threshold range can be obtained according to Eq. (12) so as to make the extruded volume of the sheet metal uniformly change and increase the formability of the sheet parts.

$$n_{i+1,j} = \frac{v^*_{i+1,j}}{\Delta v} \tag{11}$$

$$F = n \cdot F_0 \tag{12}$$

Table 2 Feed speed of model 2

Forming angle (°)	Feed speed (mm min^{-1})
60	700
50	1300
40	1600
30	2000

Table 3 Material mechanical property parameters

Name	Density (kg m^{-3})	Elastic modulus (Gpa)	Poisson ration	Yield stress (Mpa)	Tangent modulus (Gpa)	Hardening parameter
Sheet	2700	55.94	0.324	153.6	2.9	0.19775
Extrusion tool head	8160	218	0.30	–	–	–
Support mold	7810	212	0.29	–	–	–

2.3 Case studies

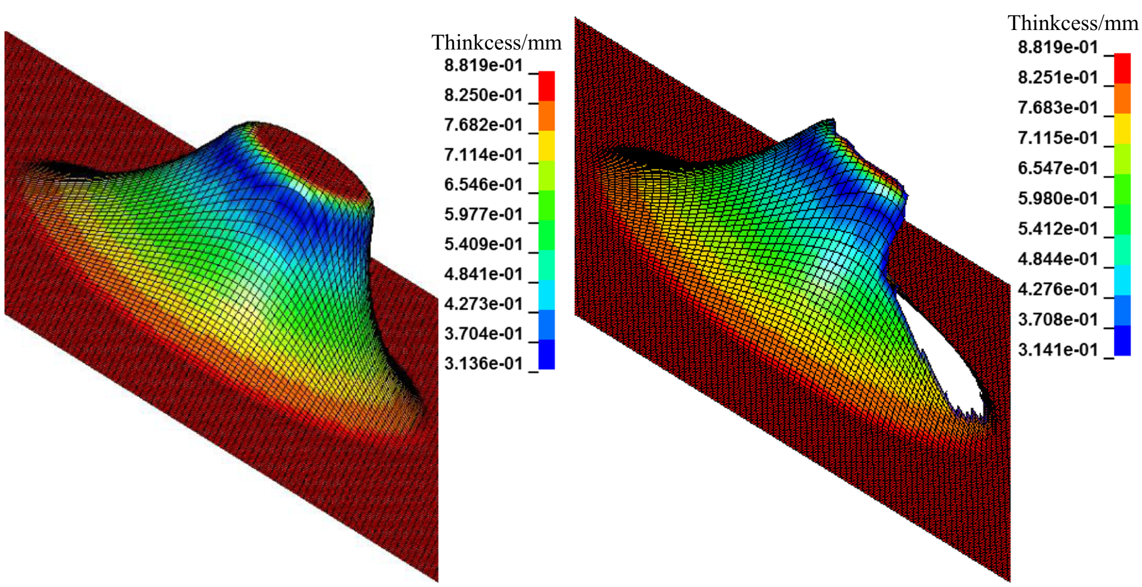
In order to verify the feasibility of the proposed algorithm, the software system of the algorithm had been implemented using C++, VC++6.0, and OpenGL graphics library on the Windows 7 environment. The system has the functions of the STL model visualization, deformed sheet metal volume calculation, feed speed determination, and NC code output. Figure 5 shows the user interface of the system.

In these case studies, model 1 shown in Fig. 6 was taken as the test model to verify the influence of the unequal feed speed on the formability of the sheet part, in which Fig. 6a is a top view of model 1 and Fig. 6b shows the profile size of the inner surface of model 1. The depth of the model is 47 mm, the diameter of the model at the opening is 110 mm, and the diameter of the model at the bottom is 31 mm. The forming angle increases from 20° to 80° with the increasing of the depth of the model.

Taking the contour path with 0.2-mm layer distance and 2000 mm/min empirical feed speed as example, the feed speed for the forming of model 1 is divided into two grades using the above algorithm. Table 1 shows the relationship between the feed speed of the extrusion tool head and the depth of the mold as well as the forming angle.

For model 1, the total length of the contour path generated is 37,400 mm and the forming time is 18.7 min when the forming is performed using the unequal feed speed determined by the above algorithm. The constant feed speed was 2020 mm/min when the forming time with the constant feed speed was same as the contour path forming time with unequal feed speed. The effect of the unequal feed speed on the profile precision, surface quality, and forming efficiency is evaluated by taking model 2 shown in Fig. 7, in which Fig. 7a is a top view of model 2 and Fig. 7b shows the profile size of the inner surface of model 2.

The maximum depth of the model is 36 mm, the diameter of the model at the opening is 140 mm, and the diameter of the model at the bottom is 62 mm. Moreover, when the depth of model 2 is between 0 and 9 mm, the forming angle is 60°; when the depth is between 9 and 18 mm, the forming angle is 50°; when the depth is between 18 and 27 mm, the forming angle is 40°; and when the depth between 27 and 36 mm, the forming angle is 30°.



(a) (b)

Fig. 8 Simulated parts of model 1. **a** Unequal feed speed. **b** Constant feed speed

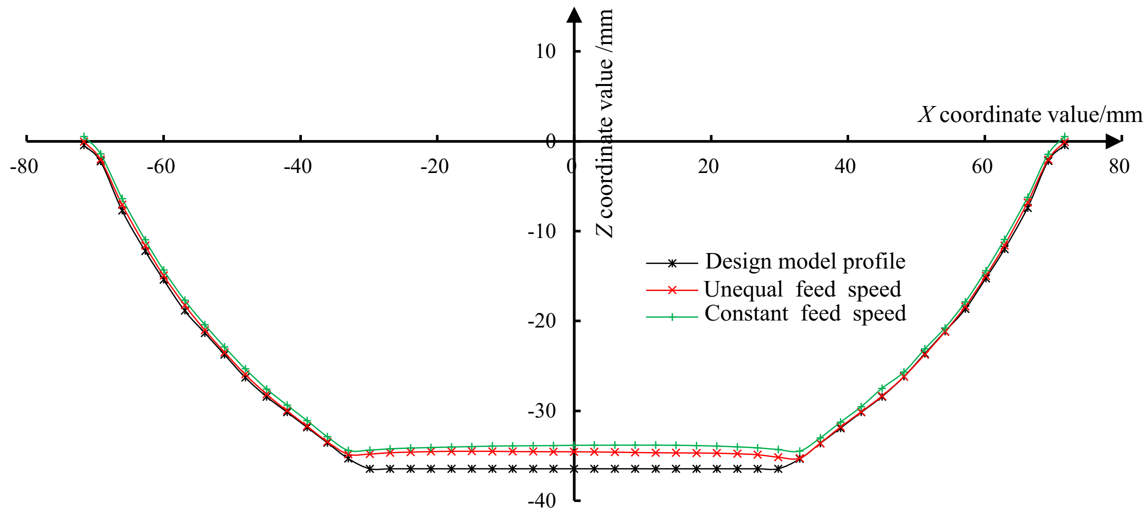


Fig. 9 Simulated profile of model 2

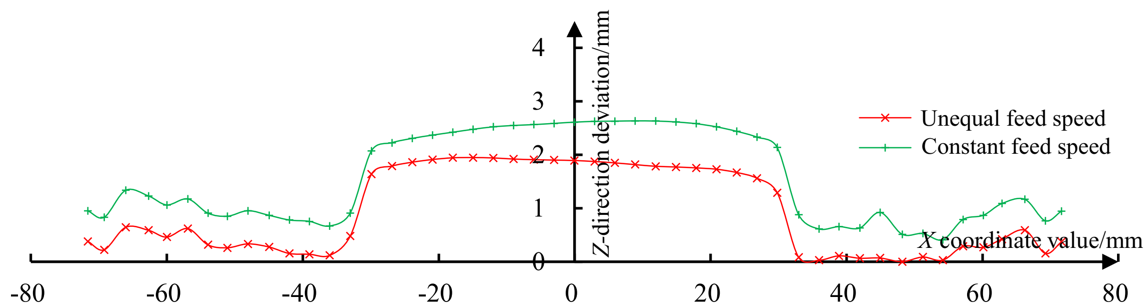


Fig. 10 *Z*-direction deviation curves

Taking the contour path with 0.2-mm layer distance and 1000 mm/min empirical feed speed as example, the feed speed for the forming of model 2 is divided into four grades using the above algorithm. The maximum feed speed is 2000 mm/min, and the minimum feed speed is 700 mm/min. The feed speed of the extrusion tool head varies with the change of the forming angle. Table 2 shows the feed speed of the extrusion tool head in each forming angle region.

For model 2, the total length of the contour path is 58,477 mm. When the forming is performed using the unequal feed speed determined by the above algorithm, the time consumed is 52.3 min. When the forming is carried out by using the empirical feed speed, the time consumed is 58.5 min. The determined constant feed speed is 1120 mm/min, when the forming time based on the constant feed speed is the same as the forming time based on the unequal feed speed.

3 The finite element analysis

In order to analyze the effectiveness of the unequal feed speed in the CNC incremental forming, the numerical simulation of the forming was conducted using the unequal feed speed and constant feed speed (the constant feed speed is the empirical feed speed) respectively, which took the sheet parts model shown in Figs. 6 and 7 as an example by using the ANSYS/

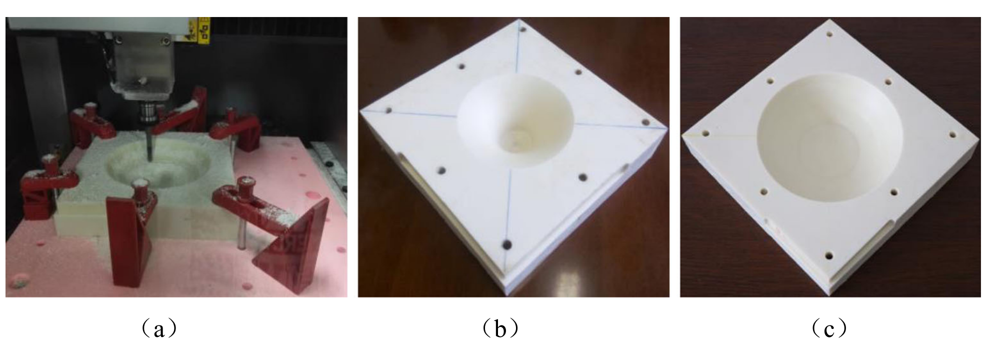


Fig. 11 Support. **a** Milling process. **b** Support 1. **c** Support 2

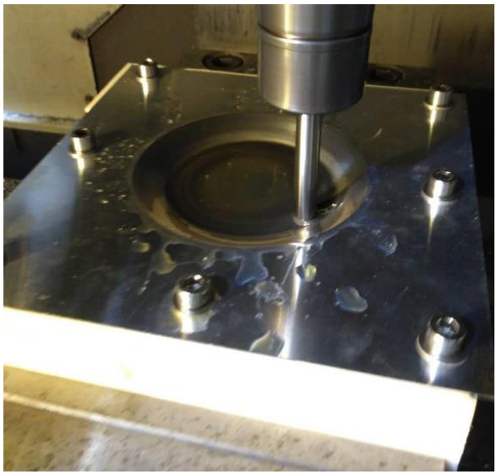


Fig. 12 Forming experiment of model 1

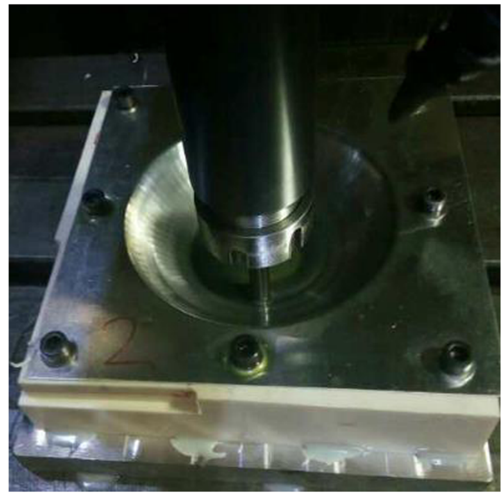


Fig. 14 Forming experiment of model 2

LS-DYNA finite element analysis software. In the numerical simulation, the effects of the feed speed on the sheet parts profile accuracy and formability were mainly analyzed.

In the analysis, the 1060 aluminum sheet with a thickness of 0.88 mm was selected as the forming sheet; the sheet metal type is set to the SHELL163 shell element. The sheet metal was divided into 1.5-mm meshes by using the mapping meshing method and the Belystchko-Wong-Chiang algorithm is used to do explicit calculation. Extrusion tool head is replaced by a ball with a diameter of 10 mm and its material is defined as W6Mo5Cr4V2 high-speed steel. The support mold material is defined as GCr15 mold steel. The extrusion tool head and support mold are set to the SOLID164 entity unit, and they were divided into 1.5- and 4-mm meshes respectively by using free mesh method. The mechanical properties of the materials are shown in Table 3.

Due to the complex forming path cannot be directly loaded onto the extrusion tool head in the finite element analysis, the forming path and feed speed need to be converted into the data that can be identified by the finite element analysis software. According to the distance between two adjacent points on the path and the feed speed, find out the time t of the forming tool head movement between the adjacent two points on the path, and sequentially accumulate time t, then the forming path and each path point corresponding to the forming time T are output to the Excel table.

In this way, the time difference between every two adjacent path points can reflect the real feed speed of the forming tool head in the CNC incremental forming. The coordinate values and the time of each path point are imported into the array corresponding to X, Y, Z, and T using the array read-in function provided by the ANSYS analysis software. In order to study the influence of the unequal feed speed on the formability, the numerical simulation analysis is conducted based on the unequal feed speed and constant feed speed by taking model 1 shown in Fig. 6 as an example. In the numerical simulation based on the constant feed speed, the sheet part ruptures while the numerical simulation is carried out to 139 steps, i.e., the forming depth of the sheet part is 36.7 mm.

The numerical simulation is carried out to the same depth without the sheet part rupturing when the unequal feed speed is used, as shown in Fig. 8. Figure 8a is the sheet part simulated by using the unequal feed speed. Figure 8b is the sheet part simulated by using constant feed speed.

In order to study the effect of the unequal feed speed on the profile dimensional accuracy of the sheet parts,

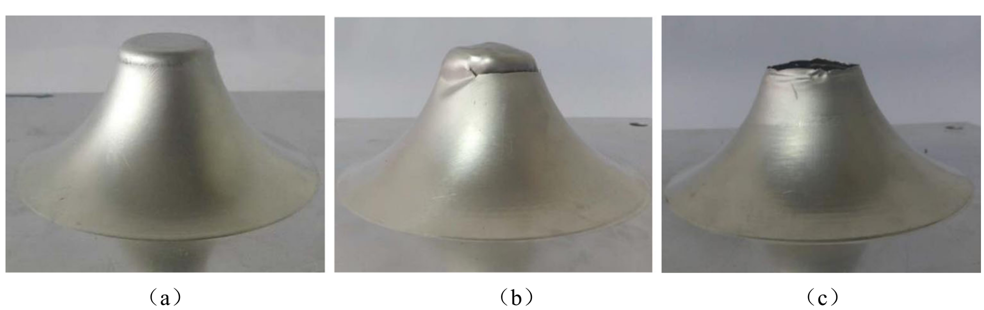


Fig. 13 The experimental parts of model 1. **a** Unequal feed speed. **b** Constant feed speed (partial broken). **c** Constant feed speed (full broken)

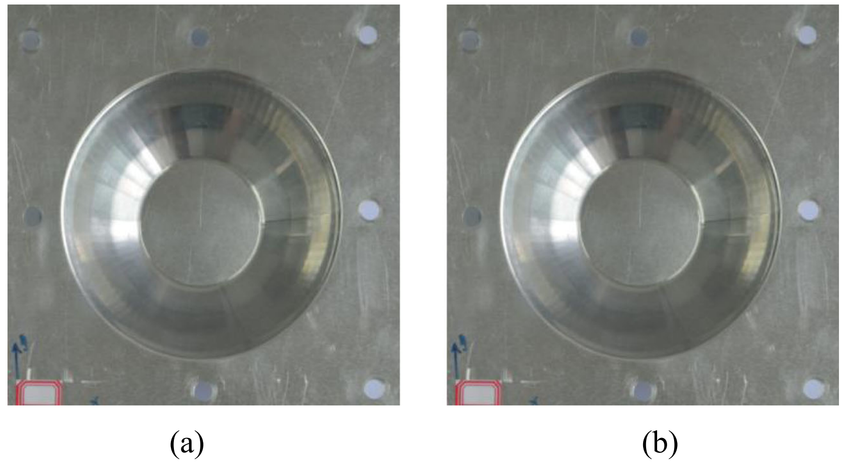


Fig. 15 The experimental parts of model 2. **a** Unequal feed speed. **b** Constant feed speed

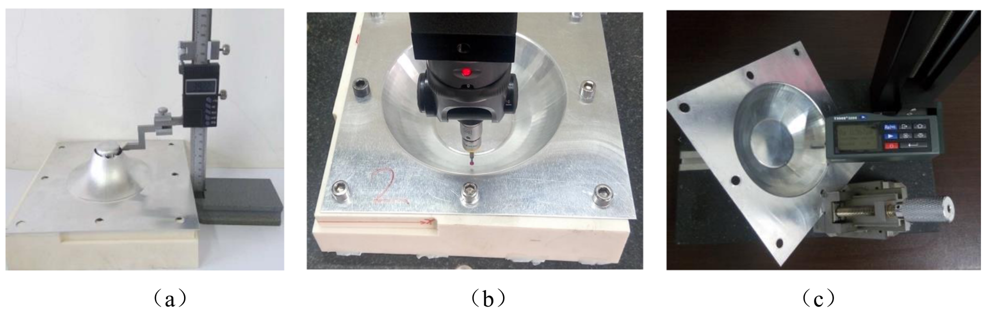


Fig. 16 Measurement. **a** Forming depth. **b** Profile size. **c** Roughness

the numerical simulations are carried out based on the unequal feed speed and constant feed speed by taking model 2 shown in Fig. 7 as an example. Because the simulated profile of the sheet parts is the profile of the neutral surface, the inner surface of the design model is offset backwards by the distance of the half thickness of the sheet metal along the normal direction of the inner surface to obtain the neutral surface of the design model.

Then, on the cross section of the neutral surface $Y=0$ on the design model, find the points that are equal to the X coordinate value on the middle cross section of the simulated, and finally calculate the coordinates value of each point on the neutral surface of the design model.

The profile curves of the simulated sheet parts based on the unequal feed speed and constant feed speed are drawn in Excel as shown in Fig. 9.

In order to further compare the difference between the profiles, the Z-direction deviation curve on the $Y=0$ cross section of the simulated profile and the neutral surface profile of the design model are plotted in Excel, as shown in Fig. 10. As can be seen from Fig. 10, the Z-direction deviation value of the simulated profile based on the unequal feed speed is less than that of the simulated profile

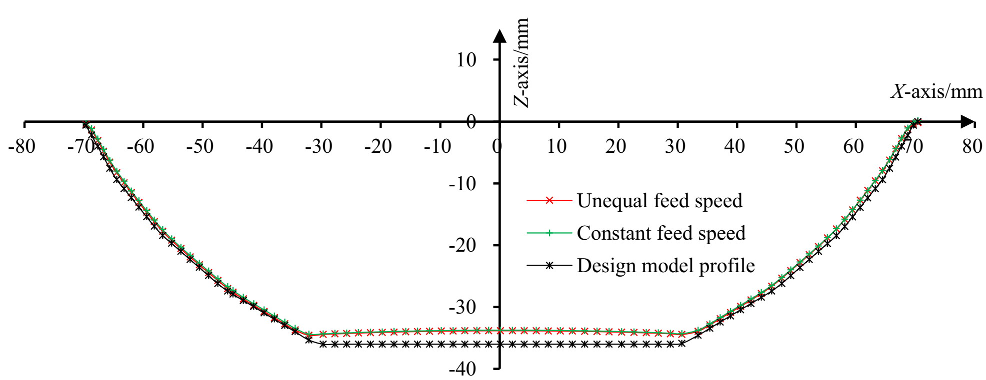


Fig. 17 Intermediate profile curves of the internal surfaces

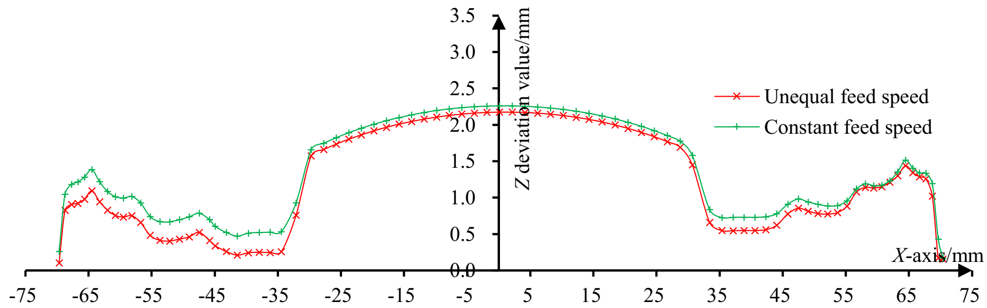


Fig. 18 *Z*-direction deviation curves

based on the unequal feed speed. The maximum *Z*-direction deviation value of the simulated profile based on the unequal feed speed is 1.947 mm, the minimum deviation value is 0.001 mm, and the average deviation value is 1.173 mm. The maximum *Z*-direction deviation value of the simulated profile based on the constant feed speed is 2.633 mm, the minimum deviation value is 0.411 mm, and the average deviation value is 1.323 mm.

4 Forming experiment and measurement

4.1 Forming experiment

In order to analyze the effects of the unequal feed speed on the forming, taking the sheet parts model shown in Figs. 6 and 7 as an example, the CNC incremental forming experiments were carried out based on the unequal feed speed and the constant feed speed determined by the above algorithm respectively. The whole forming experiments have been conducted using three-axis machining center. The support is fabricated by milling process on the mold machine using the nylon plate. Figure 11a shows the milling process of the support. Figure 11b, c shows the actual support fabricated by the CNC milling.

In the CNC incremental forming experiment, the 1060 aluminum sheet with the thickness of 0.88 mm was selected as the sheet metal to be formed. The extrusion tool head was made of W6Mo5Cr4V2 high-speed steel and the diameter of the forming tool is 10 mm. The machine oil was used as the lubricants.

For the forming of model 1 shown in Fig. 6, the empirical feed speed is usually selected as 2000 mm/min. When the forming is conducted using the unequal feed speed, the feed speed of the extrusion tool head in each region of the sheet part is shown in Table 1. When the forming is conducted using the constant feed speed, the feed speed of the extrusion tool head is 2020 mm/min, and the forming process is shown in Fig. 12. Figure 13 shows the formed experimental parts, in which Fig. 13a is an experiment part formed with unequal feed speed, Fig. 13b, c is the broken case of the experiment parts formed with the constant feed speed, one is the partial broken, and another is the full broken.

For the forming of model 2 shown in Fig. 7, the empirical feed speed is selected as 1000 mm/min. When the forming is conducted using the unequal feed speed, the feed speed of the extrusion tool head in each region of the sheet part is shown in Table 2. When the forming is conducted using the constant feed speed, the feed speed of the extrusion tool head is 2020 mm/min; the forming process is shown in Fig. 14. Figure 15 shows the formed experimental parts, in which Fig. 14a shows the experimental part formed with unequal feed speed, and Fig. 14b shows the experimental part formed with constant feed speed.

4.2 Measurement

As shown in Fig. 16, the profile size and the surface roughness of the experimental parts shown in Fig. 15 were measured by the three coordinate measuring machine and the roughness instrument respectively. The forming depth of the experimental parts shown in Fig. 13 was measured by the height measuring machine. Figure 16a shows the forming depth measurement of the sheet part rupture using the height measuring instrument. Figure 16b shows the profile dimensions measurement of the experimental parts using the three coordinate measuring machine. And Fig. 16c shows the roughness measurement of the surface quality of the experimental parts using the roughness instrument.

Table 4 Profile arithmetic mean deviation value *Ra*

Forming angle (°)	*Ra* with unequal feed speed forming	*Ra* with constant feed speed forming
60	0.209	0.249
50	0.288	0.322

Table 5 Profile maximum height value *Rz*

Forming angle (°)	*Rz* with unequal feed speed forming	*Rz* with constant feed speed forming
60	0.609	0.78
50	1.202	0.943

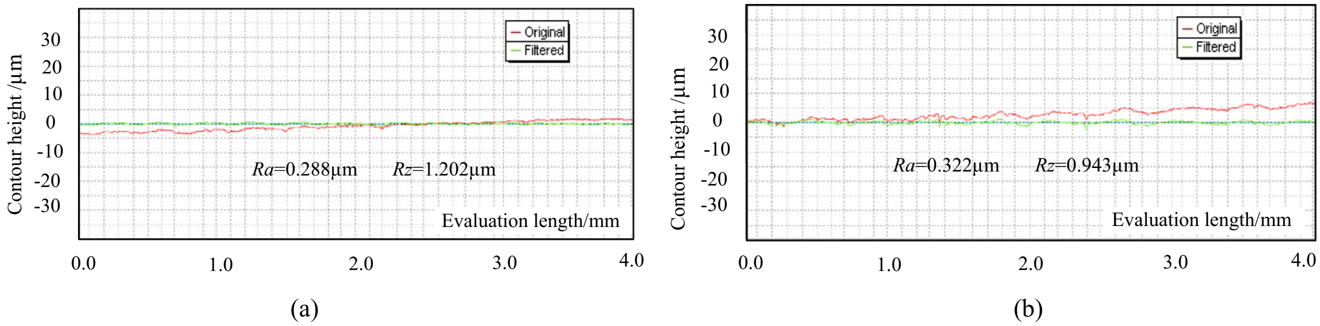


Fig. 19 Roughness. **a** Part formed with unequal feed speed. **b** Part formed with constant feed speed

Through measuring the forming depth of the experimental parts shown in Fig. 13, it was found that the sheet part forming depth is 47 mm and the sheet part had not been ruptured when the sheet part was formed using the unequal feed speed forming. The sheet part had been ruptured when the forming was conducted using the constant feed speed. In order to prevent the experimental result from being accidentals, the experiment was repeated and it was found that the sheet part had been ruptured when the sheet part was formed using the constant feed speed. The experimental results are shown in Fig. 13b, c. Figure 13b shows that the experimental part 1 was broken when the forming depth was 39.4 mm. As shown in Fig. 13c, the experiment part 2 was bursts when the forming depth was 41.8 mm. It can be seen that the unequal feed speed can effectively improve the formability.

In measuring the profile size of the experimental part, the coordinates of the profile node of the experiment parts shown in Fig. 15 were measured by using the three coordinate measuring machine with an interval of 2 mm on the *X* coordinate axis (that is, on the cross section of $Y = 0$), and the profile curves were drawn (Fig. 17). At the same time, the deviation curves between the experimental parts profile and the designed model profile in the *Z*-axis direction are drawn, as shown in Fig. 18. It can be seen from Fig. 18 that the profile deviation of the sheet part formed by using the constant feed speed is greater than the profile deviation of the sheet part formed with the unequal feed speed.

The maximum deviation value of the profile formed with the constant feed speed is 2.26 mm, the minimum deviation value is 0.17 mm, and the average deviation value is 1.32 mm. The maximum deviation value of the profile formed by the unequal feed speed is 2.17 mm, the minimum deviation value is 0.1 mm, and the average deviation value is 1.17 mm.

Tables 4 and 5 show the average value of the measured arithmetic mean deviation value *Ra* and the maximum height value *Rz* of the profile is obtained respectively by measuring the surface roughness of the formed parts. It can be seen that the overall surface quality of the sheet part formed with the unequal feed speed outperforms that of the sheet part formed with the constant feed speed. When the forming angle of the sheet part is 50°, although the profile maximum height value *Rz* of the formed sheet part based on the unequal feed speed is larger than that based on the constant feed speed, the difference between the two values is relatively small. In addition, the arithmetic average deviation *Ra* of the profile of the sheet part formed by using the unequal feed speed is smaller, as shown in Fig. 19.

5 Conclusion

In the CNC incremental forming, for the regions with different surface characteristics, if the unequal feed speed that is adaptive to the surface feature is adopted, the sheet part profile accuracy, surface smoothness, and formability can be improved compared with the constant feed speed under the same forming efficiency. The proposed determination algorithm of the unequal feed speed based on the threshold of the sheet metal volume change rate can divide the curved surface into the several regions according to the surface characteristics of the sheet metal part and determine the corresponding feed speed for them. The software system runs reliably and stably.

The proposed method of the finite element analysis for the CNC incremental forming based on the unequal feed speed is studied, which can be applied to the numerically simulation for the CNC incremental forming process based on the unequal feed speed. In this paper, the modular processing method of the sheet metal volume change rate threshold has some randomness and needs some experience of the user. It is necessary to further study the issue in the future to improve its reliability.

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