Continuous Forming System for Forming 3D Surface Parts and Its Finite Element Model

Mi Wang a, Shuchen Yang a,* and Guolong Lu b

a Engineering College, Changchun Normal University, Changchun, Jilin Province, 130022, P. R. China.
b Key Laboratory of Bionic Engineering (Ministry of Education), College of Biological and Agricultural Engineering, Jilin University, Changchun, Jilin Province, 130022, P. R. China.

*Ysc2017@mail.cnnc.edu.cn

Abstract. Continuous forming system (CRS) is a novel technique for manufacturing 3D surface parts. CRF employs two flexible rolls to generate deformation by controlling roll gap between two flexible rolls. Finite element model is set up to investigate the CRF process. The influence of maximum height difference and maximum compression ratio difference in cross-section has been investigated. The accuracy of the longitudinal was demonstrated through numerical simulations. CRF experiments were performed and the results show the shape of the formed part is in good agreement with the shape of the desired part.

1. Introduction

3D surface parts are widely used in modern architectures. For many years, tamping, stretch-bending, hydroforming have been used to form three-dimensional surface parts. Nevertheless, large initial investments and long setup time are needed in these forming processes, making them only profitable for mass production. Yoon and Yang [1,2] explored an incremental roll forming design using one centre roll and two pairs of support rolls to manufacture 3D surface parts, which is very suitable for single and small batch products. However, it is low in productivity and the formed part has large thickness reduction. Shim et al. [3-5] proposed discrete-rolls forming which is time-saving for small batch production. The discrete-roll is composed of small rolls arranged in a linear array. Each small roll can rotate around its curved axis, and the shape of forming roll can be adjusted by changing the height of each small roll. Li et al. [6,7] proposed flexible roll forming based on three roll-bending process, and the sheet metal can be bent simultaneously in transverse and longitudinal directions. Cai et al. [8,9] proposed the CRF process using two roll for manufacturing 3D surface parts. In the present paper, the finite element model is established with the aim of investigating the forming accuracy of CRF numerically.

2. Continuous roll forming system and Finite element model

2.1 Principle of continuous roll forming

Continuous roll forming (CRF) system employs two flexible roll to generate deformation in transverse and longitudinal directions. Figure 1 shows a schematic diagram of CRF equipment. The height of control unit on the flexible roll can be adjusted, resulting in curvature and roll gap changing [10,11]. In
forming process, the flexible roll rotate around its curved axis and a flat sheet metal is manufactured into a desired part [12].

2.2 Finite element model of CRF
Finite element model of CRF process was performed based on dynamic explicit FEM under ABAQUS/Explicit environment [13-16]. The sheet metal was meshed by C3D8R element. Relevant material properties are: Young’s modulus $E = 207$ GPa, yield stress $\sigma_s = 91$ MPa, Poisson’s coefficient $\mu = 0.29$ and density $\rho = 7845$ kg/m$^3$. The flexible roll was established using R3D4 elements. Figure 2 shows the schematic diagram of 1/2 finite element model from the symmetrical axis (xx’) to the outer edge.

A typical CRF process is shown in figure 3. At the first step, the upper flexible moves downward, and sheet metal is pressed by the flexible rolls. At the second step, flexible roll rotates on its curved axis and sheet metal is bent in two directions. With the rotation of flexible rolls, 3D surface parts are formed eventually.
2.3 Results of numerical simulation analysis

Plentiful simulated results were presented to compare with the obtained results based on the theoretical calculation. The central function of the flexible roll is calculated according to the transverse curvature of the desired part.

\[ z(y) = \rho_T \left[ 1 - \sqrt{1 - \left( \frac{y}{\rho_T} \right)^2} \right] \]  

(1)

In which, \( \rho_T^{-1} \) is the transverse curvature, \( y \) is the coordinate in transverse direction.

The distributions of the roll gap are different for saddle parts and torus parts. For a saddle part, the distribution of the roll gap is wide in middle section, for a torus part, the distribution of the roll gap is narrow in middle section, respectively. In order to form a saddle part, the height of the control unit is minor adjusted based on equal 2. A torus part is formed when the distribution of the roll gap is given as equal 3.

\[ h(y) = \left[ 1 - \rho_T \rho_L^{-1} \frac{\sqrt{1 - \left( \frac{y}{\rho_T} \right)^2}}{\sqrt{1 - \left( \frac{y}{\rho_L} \right)^2}} \right] H \]  

(2)

\[ h(y) = \left[ 1 - \rho_T \rho_L^{-1} \frac{\sqrt{1 - \left( \frac{y}{\rho_T} \right)^2} - \sqrt{1 - \left( \frac{y}{\rho_L} \right)^2}}{\sqrt{1 - \left( \frac{y}{\rho_L} \right)^2}} \right] H \]  

(3)

In which, \( H \) is the thickness of the sheet metal.

To evaluate the accuracy of relationship between calculation curvature \( \rho_L \) and simulation curvature \( \rho_L' \), shape error ratio \( e_L \) is defined as shape difference between calculation curvature \( \rho_L \) and simulation curvature \( \rho_L' \).

\[ e_L(y) = \left| \frac{\rho_L' - \rho_L}{\rho_L} \right| \]  

(4)

2.3.1 Case 1: saddle part. Finite element model of CRF is established, in order to form a saddle part, the position of short rigid roll is minor adjusted based on equal 2. Figure 4 presents calculation curvatures and simulation curvatures of saddle part under a series of maximum height difference \( \gamma \) and maximum compression ratio difference \( \delta \). Figure 4(a) shows calculation curvatures and simulation curvatures of saddle parts under same \( \gamma \), which is 13.864 mm. Shape error ratio is small, the maximum value of \( e_L \) is 9.64%, the average of \( e_L \) is 5.43%.

![Figure 4. Simulation curvature for saddle parts.](image)

(a) same maximum height difference γ (b) same compression ratio difference δ
Figure 4(b) shows calculation curvatures and simulation curvatures of saddle parts under same $\delta$, which is 0.0525. Shape error ratio is small, the maximum value of $e_L$ is 8.26%, and the average of $e_L$ is 5.62%. Dates in figure 4 clearly demonstrate that CRF can be controlled to form saddle part based on equal 2, and prove the relationship between longitudinal curvature of saddle part and $\gamma/\delta$.

2.3.2 Case 2: torus part. A torus part is formed by minor adjusting the position of short rigid roll based on $e_{qual3}$. Simulation results of CRF for torus part under a series of maximum height difference $\gamma$ and maximum compression ratio difference $\delta$ are shown in figure 5. Figure 5(a) shows calculation curvatures and simulation curvatures of torus parts under same $\gamma$, which is 13.864 mm. Shape error ratio is small, the maximum value of $e_L$ is 9.49%, the average of $e_L$ is 5.36%.

Figure 5(b) shows calculation curvatures and simulation curvatures of torus parts under same $\delta$ (0.0593). Shape error ratio is small, the maximum value of $e_L$ is 9.39%, the average of $e_L$ is 4.32%. Dates in figure 4 clearly demonstrate that CRF can be controlled to form torus part based on equal 3, and prove the relationship between the longitudinal curvature of torus part and $\gamma/\delta$.

3. Conclusions
Continuous roll forming has been developed to manufacture 3D surface part. The longitudinal curvature can be controlled by the gap between upper and lower flexible rolls. The influence of maximum height difference $\gamma$ and maximum compression ratio difference $\delta$ in cross-section has been investigated. According to $\gamma$ and $\delta$, longitudinal curvature of formed part can be calculated. Extensive numerical simulations of CRF processes had been performed by dynamic explicit finite element methods, a series of numerical results were obtained. These results reveal the relationship between longitudinal curvature of formed part and $\gamma/\delta$.

References
[1] Yoon SJ and Yang DY. Development of a highly flexible incremental roll forming process for the manufacture of a doubly curved sheet metal. Cirp Ann-Manuf Technol 2003; 52(1): 201-4.
[2] Yoon SJ and Yang DY. An incremental roll forming process for manufacturing doubly curved sheets from general quadrilateral sheet blanks with enhanced process features. Cirp Ann-Manuf Technol 2005; 54(1): 221-4.
[3] Shim DS, Yang DY, Han MS, Chung SW, Kim KH, and Roh HJ. Experimental study on manufacturing doubly curved plates using incremental rolling process. ICTP 2008 (The 9th International Conference on Technology of Plasticity), Korea 2008; 2378-83.
[4] Shim DS, Yang DY, Kim KH, Han MS, and Chung, SW. Numerical and experimental investigation into cold incremental rolling of doubly curved plates for process design of a new LARS (line array roll set) rolling process. Cirp Ann-Manuf Technol 2009; 58(1): 239-42.

[5] Shim DS, Yang DY, Kim KH, Chung SW, and Han MS. Investigation into forming sequences for the incremental forming of doubly curved plates using the line array roll set (LARS) process. Int J of Mach Tool Manuf 2010; 50: 214-8.

[6] Cai ZY, Li MZ. The principle and theoretical analysis of continuous roll forming for three-dimensional surface parts. Sci China Technol Sci 2013; 56(2): 351-8.

[7] Cai ZY, Li MZ, Lan YW. Three-dimensional sheet metal continuous forming process based on flexible roll bending: the principle and experiments. J Mater Process Technol 2012; 212(1): 120-7.

[8] Li MZ, Cai ZY, Li RJ, Lan LW, Qiu NJ. Continuous forming method for three-dimensional surface parts based on the rolling process using bended roll. J Mech Eng 2012; 48(14): 44-9.

[9] Cai ZY, Li MZ. Mechanical mechanism of continuous roll forming for three-dimensional surface parts and the calculation of bending deformation. J Mech Eng 2013; 49(2): 35-41.

[10] Li MZ, Hu ZQ, Cai ZY, Gong XP. Method of efficient continuous plastic forming for freeform surface part. J Jilin Univ (Eng Technol Ed) 2007; 37(3): 489-94.

[11] Li MZ, Cai ZY, Sui Z, Li XJ. Principle and applications of multi-point matched-die forming for sheet metal. Proc Inst Mech Eng B: J Eng Manuf 2008; 222(5): 581-9.

[12] Dong YG, Zhang WZ, Song JF. Theoretical and experimental research on the elongation law of the rail in rail rolling by a universal mill. J Mech Eng 2010; 46(6): 87-92.

[13] Cai ZY, Lan YW, Li MZ. Continuous sheet metal forming for doubly curved surface parts. Int J Precis Eng Man 2012; 13(11): 1997-2003.

[14] Zeng J, Liu ZH, Champliaud H. FEM dynamic simulation and analysis of the roll-bending process for forming a conical tube. J Mater Process Technol 2008; 198(1-3): 330-43.

[15] Feng GK, Champliaud H. Modeling and simulation of asymmetrical three-roll bending process. Simul Model Practr Th 2011; 19(9): 1913-7.

[16] Cai ZY, Wang SH, Hong XP, Li MZ. Numerical simulation for the multi-point stretch forming process of sheet metal. J Mater Process Technol 2009; 209(1): 396-407.