A Numerical Study on Chain-Die Forming of the aluminium profiles with variable cross-section

K Lu¹, Z Liang¹, Y Liu¹, T Zou¹, D Li¹, S Ding²

¹ State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China

² School of Mechanical and Mining Engineering, The University of Queensland, St Lucia, Brisbane, QLD 4072, Australia

lukaijun001@126.com, txzou1984@163.com

Abstract. Roll forming is a widely used forming process of profile with constant cross-section because of its high quality, high efficiency, and low cost. However, variable cross-section profiles are becoming more common with the development of the vehicle industry while the demand can’t be met by the traditional roll forming technique. Chain-die forming is a newly introduced technique to deal with the problem. Chain-die forming extends the deformation zone by enlarging the rotation radii of the moulds. The study focused on the finite element simulations of chain-die forming aluminium profiles with variable cross-section and the comparation with high strength steels. The results showed the influence of materials such as anisotropy on wrinkling and scratch in chain-die forming and verify the finite element simulation in predicting the chain-die forming results.

1. Introduction

Yuankun Zhang and Shichao Ding[1] firstly developed chain-die forming technology in 2012 to replace roll forming. Compare with roll forming, it has advantages of lower redundant strain during forming and almost zero residual stresses in products. Yuankun Zhang and Shichao Ding[2] firstly showed that the china die forming is a derivation of roll forming which has larger virtual radii, indicating that the chain-die forming can achieve more bending in a single pass and less end-flare compared with roll forming. Shichao Ding and Yuankun Zhang[3] summarized that the chain-die forming has 5 advantages over roll forming: less energy, simpler die design and less forming passes, simpler tooling design and alignment, no slippage, variable cross sectional products.

Compare with roll forming, the main advantage of chain die forming is small redundant strains, which is caused by its different longitudinal strain evolution during forming. Yuankun Zhang and Shichao Ding[4] utilized finite element analysis to simulate the forming process of an AHSS U-channel, and verify the result by experiments.

The low longitudinal strain is the main characteristic of the Chain-die forming technology. Yong sun et al.[5] studied the longitudinal strain of Chain-die forming experimentally, indicating that the peak longitudinal strains usually occurred when about 20% of the products’ are formed in longitudinal direction. Yong sun et al.[6] analysed the longitudinal strain of chain die forming products with variable widths analytically by establishing a new mathematical model, and validate the model experimentally. Yong sun et al.[7] utilized response surface methodology to study the flange height and
thickness on the maximum edge longitudinal membrane strain, pointing that the strain is primarily controlled by the flange height. Yong sun et al.[8] utilized the finite element method to simulate the Chain-die forming and roll forming respectively, indicating that Chain-die forming can achieve more bending in one pass with no defects due to its less residual stress over roll forming. Yong sun et al.[9] established an analytical model to describe the longitudinal strain development during Chin-die forming process, indicating that the peak longitudinal strain is influenced by flange height and bottom die’s round corner radius, while the position of the peak longitudinal strain is only influenced by the virtual roll radius. Zhenye Liang et al.[10] studied the feasibility of Chain-die forming of none-uniform product, and attribute the warping to insufficient longitudinal deformation. Zhen Qian et al.

The main defects of chain die forming is the springback, which occur both in cross section and longitudinal line. Zhen Qian et al.[11] studied the influence of five variables on the products’ flange angle in several cross sections, pointing that the key factor influencing the average flange angle is the virtual forming gap, while the key factor influencing the variation of the flange angle is the virtual roll radius. Zhen Qian et al.[12] investigated the Chain-die forming of AHSS U-channel profile and indicated that the average flange angle is primarily controlled by the forming gap. Yaguang Li et al.[13] introduced the Chaboche hardening model to describe the AHSS material and compared the Chain-die forming and roll forming systematically. Yaguang Li et al.[14] modified Chaboche hardening model to better describe AHSS’s hardening behaviour. Based on the new material model, an analytical model to predict the U channel’s springback is established to provide an much more effective method for the die block’s optimization.

In the past studies, the material is usually high strength steel (AHSS), and the hardening rules of the material which is adopted in the finite element analysis is usually isotropic. In this study, an aluminium variable-width hat-channel product was designed. Both experiments and simulation were conducted to investigate the feasibility of chain-die forming on aluminium sheet. Results were analysed to illustrate the behaviour, including wrinkling and scratch.

2. Methodology

2.1. Chain-die forming technology

The main mechanisms of the chain-die forming machine includes the rack board, rollers, gears, chains and die blocks, as illustrated in Figure 1. Track boards with large radius are mounted to provide working surfaces for die blocks’ movements. The linked chains are mounted around the outer surfaces of two track boards, the rollers fill between chains and track boards for the reduction of the friction. All die blocks are mounted on chains in order and move with their corresponding chains during forming. During the forming, the chains and the die blocks mounted on them are both driven by the gear. The sheet is formed gradually with the engagement of two pairs of blocks.

![Figure 1. Schematic illustration of the Chain-die forming machine](image-url)
During the forming process, two chains links around the upper and lower track boards are driven synchronously by the gear, leading two groups of die blocks moving along circular paths with extremely large radius. The sheet metal is firstly fed in manually and trapped on its head, and then formed incrementally with the engagement of the upper and lower die blocks.

2.2. Profile of the products
Figure 2 shows the geometry of the variable width hat channel profile and the design parameter for the bottom die blocks, and the thickness of the profile is 1.2 mm.

![Figure 2](image)

Figure 2. (a) Geometry, (b) dimensions of bottom die blocks.

The chain-die forming of half the profile with QP1180 sheet metal has been studied by Zhenye Liang, and no defect such as wrinkling or scratch was found before. The geometry of the half profile is shown in Figure 3.

![Figure 3](image)

Figure 3. Geometry of half the profile

2.3. Simulation set-up
The chain-die forming of none-uniform profiles were simulated by ABAQUS/Standard. Python development scripts were imported to improve the efficiency. The die blocks are defined as rigid shells, while the blank is defined as deformable body.

The centre point of each block’s bottom surface is assigned as its reference moving point respectively. Through discretizing the movement of each block into translation and rotation, the forming trajectory is achieved by the aid of the python script.

The initial flat blank is meshed unevenly. Fine mesh is adopted in the region which will be bent during the forming process while coarse mesh is adopted in the web region. The workpiece is meshed
with 51873 eight node linear brick elements with reduced integration and hourglass control (C3D8R). Five mesh layers are adopted along the thickness direction to achieve better convergence and higher accuracy.

The details of the FE model of Chain-die forming processes and the mesh of the workpiece are shown in Figure 4.

![Finite element model of Chain-die forming](image)

**Figure 4** finite element model of Chain-die forming

### 2.4. Material properties of the workpiece

Material used in the FE models is the AA6082 aluminium sheet. The true plastic stress-strain curve of the material can be calculated and interpolated by Swift’s hardening law, as shown in Eq.1.

\[
\sigma_e = K (\varepsilon_e + \varepsilon_0)^n
\]

Where \(\sigma_e\) is the equivalent stress, \(\varepsilon_e\) is the equivalent strain, \(\varepsilon_0\) is the initial strain, \(K\) is the strength coefficient, and \(n\) is the strain hardening exponent.

The Hill anisotropic yield function is adopted to calculate yield stress, as shown in Eq.2.

\[
f(\sigma) = \sqrt{F(\sigma_{22} - \sigma_{33})^2 + G(\sigma_{33} - \sigma_{11})^2 + H(\sigma_{11} - \sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{31}^2 + 2N\sigma_{12}^2}
\]

Where \(\sigma_{ij}\) is the stress in each direction, and \(F, G, H, L, N\) are anisotropic coefficients.

The flow rule is

\[
d\varepsilon_p^l = d\lambda \frac{\partial f}{\partial \sigma} = \frac{d\lambda}{f} b
\]

Where, from the definition of \(f\) above,

\[
b = \begin{bmatrix}
-G(\sigma_{33} - \sigma_{11}) + H(\sigma_{11} - \sigma_{22}) \\
-H(\sigma_{11} - \sigma_{22}) + F(\sigma_{22} - \sigma_{33}) \\
-F(\sigma_{22} - \sigma_{33}) + G(\sigma_{33} - \sigma_{11}) \\
2N\sigma_{12} \\
2M\sigma_{31} \\
2L\sigma_{23}
\end{bmatrix}
\]

Thus far, we have only considered loading applied along the axes of anisotropy. To derive a more general anisotropic model in plane stress, the sheet must be loaded in one other direction in its plane. Suppose we perform a simple tension test at an angle \(\alpha\) to the x-direction; then, from equilibrium considerations we can write the nonzero stress components as

\[\sigma_{11} = \sigma \cos^2 \alpha, \sigma_{22} = \sigma \sin^2 \alpha, \sigma_{12} = \sigma \sin \alpha \cos \alpha\]

Where \(\sigma\) is the applied tensile stress. Substituting these values in the flow equations and assuming small elastic strains yields

\[
d\varepsilon_{11} = [(G + H)\cos^2 \alpha - H \sin^2 \alpha] \frac{\sigma}{f} d\lambda
\]

\[
d\varepsilon_{22} = [(F + H)\sin^2 \alpha - H \cos^2 \alpha] \frac{\sigma}{f} d\lambda
\]
\[ d\varepsilon_{33} = -[F \sin^2 \alpha + G \cos^2 \alpha] \frac{\sigma}{f} d\lambda \]  
\[ dy_{12} = [N \sin \alpha \cos \alpha] \frac{\sigma}{f} d\lambda \]  
\( (6.c) \)  
\( (6.d) \)

Assuming small geometrical changes, the width strain increment (the increment of strain at right angles to the direction of loading) is written as
\[ d\varepsilon_{a+\pi/2} = d\varepsilon_{11} \sin^2 \alpha + d\varepsilon_{22} \cos^2 \alpha - 2d\gamma_{12} \sin \alpha \cos \alpha \]  
\( (7) \)

and Lankford's \( r \) value for loading at an angle \( \alpha \) is
\[ r_{\alpha} = \frac{d\varepsilon_{a+\pi/2}}{d\varepsilon_{11}} = \frac{H + (2N - F - G - 4H) \sin^2 \alpha \cos^2 \alpha}{F \sin^2 \alpha + G \cos^2 \alpha} \]  
\( (8) \)

By altering the \( \alpha \) as 0°, 90° and 45°, the relationship between Lankford's \( r \) value in different directions and \( F, G, H, N \) is established as follow:
\[ \frac{H}{G} = r_0 \]  
\( (9.a) \)
\[ \frac{H}{F} = r_{90} \]  
\( (9.b) \)
\[ \frac{N}{G} = \left( r_{45} + \frac{1}{2} \right)(1 + \frac{r_{45}}{r_{90}}) \]  
\( (9.c) \)

In the ABAQUS, all anisotropic coefficients \( R_{ij} \) is defined with respect to a reference yield stress, \( \sigma^0 \) or \( \tau^0 \).
\[ R_{ij} = \frac{\bar{\sigma}_{ij}}{\sigma^0}, \text{when } i = j \]  
\( (10.a) \)
\[ R_{ij} = \frac{\bar{\sigma}_{ij}}{\tau^0}, \text{when } i \neq j \]  
\( (10.b) \)

Where \( \bar{\sigma}_{ij} \) is the yield stress in the specific direction. And \( \sigma^0 = \sqrt{3} \tau^0 = f(\sigma) \), which is the equivalent stress.

Assuming the uniaxial tension tests are conducted in each direction:
\[ f(\sigma) = \frac{\sigma^0}{\sigma_i} = \sqrt{G(0 - \bar{\sigma}_{11})^2 + H(0 - \bar{\sigma}_{11})^2} \]  
\( (11.a) \)
\[ f(\sigma) = \frac{\sigma^0}{\sigma_i} = \sqrt{F(0 - \bar{\sigma}_{22})^2 + H(0 - \bar{\sigma}_{22})^2} \]  
\( (11.b) \)
\[ f(\sigma) = \frac{\sigma^0}{\sigma_i} = \sqrt{F(0 - \bar{\sigma}_{33})^2 + G(0 - \bar{\sigma}_{33})^2} \]  
\( (11.c) \)

The relationship between anisotropic coefficients \( R_{ij} \) and \( F, G, H, N \) is established as follow:
\[ F + G = \frac{1}{R_{33}^2} \]  
\( (12.a) \)
\[ G + H = \frac{1}{R_{11}^2} \]  
\( (12.b) \)
\[ H + F = \frac{1}{R_{22}^2} \]  
\( (12.c) \)

\( R_{11} \) is usually set as 1, and based on Eq.8 and Eq.11, all \( R_{ij} \) can be expressed as follow:
\[ R_{11} = R_{12} = R_{23} = 1 \]  
\( (13.a) \)
\[ R_{22} = \frac{r_{90}(r_0+1)}{\sqrt{r_0(r_0+1)}}, R_{33} = \frac{r_{90}(r_0+1)}{\sqrt{(r_0+r_{90})}}, R_{12} = \frac{3r_{90}(r_0+1)}{(2r_{45}+1)(r_0+r_{90})} \]  
\( (13.b) \)

Where \( r_i \) is the anisotropy value in \( i \) direction.

The mechanical properties of the sheet(1.2mm) are listed in table 1, which is tested under 25°C.

**Table 1. Mechanical properties of AA6082 aluminum sheet**

| parameters       | abbreviation | unit | value    |
|------------------|--------------|------|----------|
| Young’s modulus  | \( E \)      | MPa  | 71000    |
| Poisson’s ratio  | \( \nu \)    |      | 0.345    |
| Yield stress     | \( \sigma_s \) | MPa  | 139.5    |
| \( R_{22} \)     |              |      | 1.092142 |
| \( R_{33} \)     |              |      | 0.936395 |
| \( R_{22} \)     |              |      | 0.982689 |
3. Results and discussions
The simulation results and the experimental results are discussed in this section. The characteristics of the chain-die forming on aluminum sheet are investigated including the defects of the wrinkling and scratch.

3.1. Analysis of wrinkling in Chain-die forming
The simulation results of the aluminum none-uniform profile are shown in Figure 5. Figure 5 (a) shows the results of actual material which consider the anisotropy, while in Figure 5 (b) the material is assumed isotropic. Compare the results of different hardening rule, it indicates that the anisotropy is the key factor affecting the profile’s wrinkling.

The experimental result of the aluminum none-uniform profile is shown in Figure 6. The ATOS Triple Scan non-contact structured blue light 3D scanner is utilized to acquire the geometry of the chain-die formed variable cross-section product, as shown in Figure 8. Then these data are processed with Geomagic studio 2013 to obtained the critical dimensions of the Chain-die formed parts.

The experimental and numerical results of profile flange’s section line is shown in Figure 7, which verify the accuracy of the simulation.
3.2. Scratch
The simulation results of product’s shear stress distribution is shown in Fig 8, indicating that scratch might occur in the stress concentration region. In ABAQUS, S12 means $\tau_{12}$.

Figure 7. Comparison between FEM and experiment of the wrinkling section line

Figure 8. FEM result of shear stress distribution
Figure 9 shows the scratches on the product, which agrees well with the simulation result.
4. Conclusions
A complex variable width aluminum hat channel profile was designed, and the feasibility of chain-die forming on aluminum was investigated with finite element method and experiments. The experimental samples were digitalized and compared with the simulation results to analyze the defects quantitatively. The following conclusions are drawn:
1) The comparison between the anisotropic and isotropic materials shows that the anisotropy of the material sheet is the main factor of product’s wrinkling.
2) The experimental and simulation results shows that the wrinkling and scratch are the main defect in chain-die forming of aluminum sheet, and the defects can be evaluated by simulation.

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