A study of cold roll forming technology and peak strain behavior of asymmetric corrugated channels

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Abstract

The peak strain (PS) of sheet metal highly affects the process design and the quality of roll formed product. Different from the traditional roll forming technology (RFT) that all the cross section contours of the product are rolled simultaneously, a symmetric RFT is developed with respect to the corrugated channels to avoid defects like tearing, twist, and redundant deformations. The behaviors of their peak strains are subsequently simulated with finite element (FE), and the effects of three factors of the rolling speed, friction coefficient, and the bending angle of roll are analyzed, respectively. Finally, both the rationality of RFT and the accuracy of final rolled product are verified by experiments. Results show that the maximum peak strains are also distinguished for their different channel width, with respect to two symmetrical channels forming simultaneously even under the same bending angle and the pressure of roll. The maximum PS of the narrow channel is significantly larger than that of the wide, and the closer to the middle channel, the greater the PS of the narrow channel, which is on the right of bending angle of the trough. Moreover, the maximum PS is mainly influenced by the friction coefficient and bending angle of the first forming pass. This can provide a reference for other design of RFT and rolled forming quality improvement of the corrugated channels.

Keywords Asymmetric corrugated channels · Roll forming technology · Finite element simulation · Peak strain

1 Introduction

Cold roll forming is a process that progressively bends a long and flat strip of sheet metal through sets of rolls mounted on consecutive roll stations. Nowadays, the roll forming is widely used for mass production contours with a constant cross section and high dimensional accuracy [1, 2].

The corrugated channels under study are first produced by aluminum sheet through the cold roll forming machine and then are spin-made into different types of sleeves for the support of aluminum coil. Compared with the rival paper sleeve, the aluminum one has the advantages of low cost, environmental protection, light weight, and high carrying capacity; see Table 1. Therefore, it has more extensive application prospect and promotion value; see Fig. 1.

However, the strain behavior of the sheet material is extremely complicated in the roll forming of the corrugated channels because of many effects of the factors like sheet materials, slippage, and friction. As the sheet metal moves through the rolls, the corrugated channels easily cause defects like tearing, hardening, and edge wrinkles once the roll forming technology is designed unreasonably.

The interests of cold roll forming so far have focused on the factors influencing the quality of roll forming product based on the V- or U-shaped symmetric section [3–5]. Since their channel number is few, both types are rolled simultaneously to improve efficiency and reduce costs. Although the corrugated channels are connected by single U-shaped section, their RFT is more complicated due to more number, smaller interval, and asymmetric width of their channels. And the mentioned RFT above will make them tear because of the sheet metal contraction interfered by the multi-section contours of rolls in roll forming process.

Su [6] has optimized the bending angle distribution function of contour plate through analyzing the effects of the bending angle, sheet thickness, and number of rolls on the plate strain. However, the relevant RFT is not extensively
related, especially in the roll forming method. Up to now, the systemic research on the RFT of corrugated channels is relatively few because of trade secrets and their roll forming quality is mainly guaranteed by experiments, which inevitably causes low efficiency and high costs in this aspect. For the purpose, in view of the corrugated channels with five U-shaped sections, a symmetric RFT is developed in the paper for the study of their peak strain behavior and quality improvement of final roll formed product.

### 2 Symmetric roll forming technology

Before analyzing the factors influencing on the quality of final rolled product, a symmetrical RFT is first developed based on the geometric size of corrugated channels; see Fig. 2a. Namely, all the forming passes are divided into three sets according to the number of channels. The middle channel 4 is first performed in the first set, then the channels 3 and 5 are simultaneously done, and the channels 2 and 6 are finally rolled into shape.

Correspondingly, the number of rolls and bending angle each of sets can be determined by Eqs. (1) and (2), which are derived by Ona et al. [7] through comparing the relationship between the shape factor and forming passes; see Table 2.

### Table 1 Performance comparison between two types of sleeves (505 mm x 20 mm x 100 mm)

| Item       | Weight (kg) | Compressive strength (N/100 mm) | Recyclable | Pollution | Price ($) |
|------------|-------------|---------------------------------|------------|-----------|-----------|
| Paper      | 28          | 2200                            | N          | Y         | 18        |
| Aluminum   | 6           | 2500                            | Y          | N         | 15        |

### Fig. 1 Two types of sleeves: a paper sleeve, b aluminum sleeve

(a) Paper sleeve  
(b) Aluminum sleeve

### Fig. 2 Geometric size and roll profile of corrugated channels. 1, left edge; 2, 3, narrow channels; 4, middle channel; 5, 6, width channels; 7, right edge
where \( \Phi \) is shape factor; \( W_1 \) is half width of strip; \( N, h, \) and \( W_2 \) are the number, height, and half width of corrugated channels; \( \theta_i \) and \( \theta_0 \) are bending angle and final bending angle of roll; and \( i \) and \( n \) are forming pass order and number, respectively.

Figure 2b shows the roll profile design of corrugated channels, correspondingly. With this symmetric RFT, the quality of final rolled product is ensured through the center line \( o_4 \) of middle channel 4 moving down continuously and the initial center lines \( o_{31}, o_{51}, o_{21}, o_{61} \) towards their final ones \( o_3, o_5, o_2, o_6 \) of channels 3, 5, or 2, 6, respectively.

### 2.1 Finite element model

FE is often used to determine main and interaction effects between controllable process settings and uncontrollable variation of incoming material properties with respect to the product defects [8, 9]. The material used for simulation in this paper is aluminum sheet 6061-T6 with width 76 mm and thickness 0.25 mm, of which performance parameters are given in Table 3. Although the length of aluminum sheet is infinite, in order to improve the simulation efficiency, only 800-mm pre-cut sheet more than 3 passes distance (roll station distance 300 mm) is hereby fed into the rolls. The rolls are set as discrete rigid bodies, and the sheet is meshed with thin shell elements S4R. Then, the assembly model of the corrugated channels is established in ABAQUS; see Fig. 3.

#### 2.2 Strain simulation

When the aluminum sheet is bitten into the first forming pass, if the corresponding center line \( o_4 \) of channel 4 deviates from that of the roll contour, two edges 1 or 7 of the final rolled corrugated channels could be too long or short, which both deteriorate the quality of sleeve. Therefore, the first pass plays a vital role during the whole forming process. Also because the quality of the final rolled channels is guaranteed by the last pass in each set of rolls, only the sheet strain behaviors of four passes will be simulated in the following section.

The friction coefficient between the sheet and roll is very difficult to define accurately. However, in order to better analyze the friction effect in actual production, Coulomb’s friction law and friction coefficient 0.1 are adopted in the simulation according to the suggestions of Paralikas et al. [10]. Then the time is set to 28 s in the STEP module according to the distance between the first and ninth passes at about 2800 mm. After the explicit dynamics algorithm is adopted, the sheet is fed into the rolls at a forming speed of 100 mm/s whereby both the top and bottom rolls are driven. Figure 4 shows the sheet strain behaviors of four forming passes. And the abscissa scope represents the sheet initial width 76 mm, of which the cross section is subdivided from the start element 459 to the end 307. Thus, the sheet strain behavior can be described by corresponding element in roll forming of the corrugated channels.

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**Table 2** Number of forming passes and bending angle of each set

| Sets | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 8th | 9th |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Passes | 43  | 75  | 90  | 43  | 75  | 90  | 43  | 75  | 90  |

**Table 3** Mechanical properties of aluminum alloy (6061-T6)

| E (MPa) | \( \mu \) | \( \sigma_y \) (MPa) | \( \sigma_s \) (MPa) | \( \rho \) (kg/m\(^3\)) |
|---------|---------|----------------|----------------|-------------|
| 69,000  | 0.33    | 275            | 355.8          | 2700        |

\[ \Phi = NW_1h/W_2 \]  
\[ \cos\theta_i = 1 + (1 - \cos\theta_0)[2(i/n)^3 - 3(i/n)^2] \]
It is seen from Fig. 4a and b that the roll forming of channel 4 is performed with three passes in the first set. Before the sheet is completely bitten by the first pass, only smaller plastic strain is produced in its trough, and the maximum PS is just 0.012. However, the plastic strains of four bending angles increase significantly in the peaks and troughs of channel 4 after it undergoes three passes in turn. Meanwhile, due to the asymmetric width of the corrugated channels, the center lines between the roll contour and the bitten sheet are not coincide along the forming direction, which causes the peak strains of these four bending angles incompletely symmetrical to the center line of the channel 4. Thus, the PS of the trough is larger than that of the crest, of which maximum value about 0.248 occurs on the right bending angle of the trough.

Although the peak strains of all the bending angles also occur in other four channels, the ones of the narrow channels 2 and 3 are significantly larger than those of the wide channels 5 and 6 even though both the channels 2 and 6 or 3 and 5 are rolled simultaneously; see Fig. 4c and d. Meanwhile, since the channel 3 is close to the middle channel 4 and is rolled earlier than the channel 2, a larger contact between its flange and the roll results in a larger friction during the contraction and slippage of the sheet. Correspondingly, the maximum PS of the channel 3 is greater than that of the channel 2, which is about 0.225 on the right of the bending angle of the trough.

Moreover, the channel 4 only plays a guiding role in the forming stages of other channels, but influenced by their roll pressure, its original strain still causes a slight slippage towards two sides, which leads to its PS smaller than the one in the first stage. However, the PS of the channel 4 remains stable after the sixth pass, which thus ensures its final rolled forming product accuracy.

2.3 Peak strain behavior analysis

Through the simulation above, the maximum PS of sheet occurs on the right of the bending angle of the channel 3 trough. Therefore, this region easily produces defects like hardening, tearing, and excessive redundant deformation. In order to further study the strain behavior of this region and better control those defects in the roll forming process of the corrugated channels, an element 17,287 of this region is used for the subsequent work. This can simplify the research without loss of generality. The stress history of this element is relatively complex caused by the extrusion, stretching, and shearing forces. It is seen from Fig. 5a that the whole process is roughly divided into three stages according to the RFT. The channel 4 is performed in the first stage, the channels 3 and 5 are in the second, and the others are in the third. Although the channel 3 is not rolled in the first stage, since influenced by the roll forming of the channel 4, the element still produces a certain stress. However, its maximum PS is lower than the yield limit stress of sheet material; hence only the pure elastic strain is produced, which disappears after the channel 4 is finally formed without any roll pressures.

However, the element stress increases abruptly from about 121 to 275 MPa in the forming direction 1100 mm. This indicates that the element has entered the second stage, and obviously, its stress law presents three cycles. In the first cycle, its maximum PS is about 322 MPa in the forming direction 1252 mm between the third and fourth passes, whereas the PS becomes small instead and is only 194.9 MPa at the contact point between the sheet and the fourth roll in the direction 1312 mm; see Fig. 6. To demonstrate this issue, Bhattacharyya et al. [11] defined the deformation length and derived the relationship between the deformation length and the metal strip thickness, flange width, and increment angle by using the minimum energy method. On the other hand, the sheet metal is clamped by the first pass before it is bitten into the second pass. Therefore, its deformation zone $\delta$ can also be illustrated by similar bending moment law of the cantilever beam. Figure 7 shows the relations between deformation length and roll force of middle channel 4. According to the force relations of cantilever beam, the bending moment $M$ can be expressed as

$$M = Fx$$

where $F$ is roll force by second pass and $x$ is deformation length.

Obviously, the bending moment $M$ becomes greater with the increasing deformation length $x$. The PS of element becomes greater, correspondingly. As for the effects of the roll station distance $d$ and other channel roll forming on the deformation length $x$ of corrugated channels, these will be carried out in the coming work.

When the element goes through the fifth and sixth passes in turn, a similar law is also produced. However, the one between the fourth and fifth passes is the largest among three maximum peak stresses, which is about 352 MPa. This is mainly because the change of roll bending angle between these two passes is greater than those of other passes, which hence results in a large force exerted on the element. With respect to the effect of bending angle, it will be further studied in Section 4. Surprisingly, although the element stress varies periodically, the corresponding strain increases like a step with the forming passes, instead.

Although the channel 3 has been performed in the last stage, the element is still subject to three periodic stresses under the roll forming of the channels 2 and 6. Since its
PS does not exceed the yield limit of sheet material all the long, its strain remains basically constant on the basis of the second stage, correspondingly.

3 Main factors influence

The effects of parameters on the PS have been done a lot based on the roll forming of single contour to control the quality of the final rolled product [12, 13]. However, the strain behavior of the corrugated channels is distinguished significantly due to their different RFT even under the
same operating conditions. Here, only three factors of the forming speed, friction coefficient, and bending angle are studied according to the actual situation with the element 17,287, respectively.

### 3.1 Forming speed

Figure 8a shows the strain behavior of the element under four different forming speeds in three stages. The element strain increases with the forming speed for the final rolled product. However, the difference of their peak strains is very small, and the biggest difference is only 0.006 between the maximum and minimum forming speeds 100 mm/s and 200 mm/s. This shows that the forming speed has little effect on the PS of the corrugated channels under the given range, and the result from simulation agrees with the conclusion obtained by Shirani et al. [14]. Through investigating the effects of some parameters on the bending defects and longitudinal strain of the symmetrical channel products, they achieved that the contact friction between the roll and sheet and the forming speed of the roll have no effect on the longitudinal strain of the side.

### 3.2 Friction coefficient

Relative to a single U-shaped section contour, of which forming is completed mainly by sheet contraction with the center line keeping the same, the forming of the corrugated channels depends on the center lines of two side channels sliding towards that of middle channel besides the sheet contraction. Thus, they are inevitably affected by the greater friction between the multi-section contour of roll in roll forming process. To avoid the sheet tearing defect, the machining precision of roll is required to be higher, and the friction coefficient between them is relatively small in the actual. Here for further analyzing the effect of friction, the friction coefficient is set as 0.1 ~ 0.25 according to the literature recommendations [10].

It is seen from Fig. 8b that the friction coefficient has a significant effect on the PS of the final rolled product. And the larger the friction coefficient, the greater the element PS. To define the influence of the friction coefficient on the PS more accurately, their corresponding data of final forming passes in the third stage is fitted with exponential curve; see Fig. 9a. And the fitting equation is expressed as:

\[ \varepsilon = 0.12199 + 0.00204e^{(12.2214/\mu)} \]  \hspace{1cm} (4)

The element PS and the friction coefficient present a non-linear relationship. Under the friction coefficient smaller than 0.15, the element PS increases gradually, and its range is no more than 0.005 by calculation with Eq. (4). However, the PS increases drastically after the friction coefficient greater than 0.15. And its difference between the minimum and maximum friction coefficients is 0.035. It must be noted that a larger friction coefficient leads to the sheet tearing easily and thus affects the forming quality of the product. And unfortunately, these results are contradicted with the conclusion obtained by Bidabadi et al. [15], which is based on the single contour roll forming. As for the reasons, they have been explained above.

### 3.3 Bending angle

Although the bending angle is the most important parameter in roll forming process [16, 17], the traditional RFT still arbitrarily sets the bending angle of each pass to produce the cross-sectional shape of the desired product based on production experience in the current production stage. With respect to the effect of bending angle \( \theta \) on the PS of corrugated channels, here four groups of bending angles are first determined according to Eq. (2), and then their increment is designed to be equal in each group of rolls to simplify the design complexity, as shown in Table 4.

As can be seen from Fig. 8c, although four groups of final bending angles are all 90°, the corresponding peak strains are significantly distinguished due to their different increments, instead. In order to further analyze the effect of bending angle of the first forming pass, the maximum peak strains of four groups of final rolled products are fitted; see Fig. 9b. And the fitting equation is expressed as:

\[ \varepsilon = 0.13303 + 0.04782(\coth(\theta - 54.64303) - 1/(\theta - 54.64303)) \]  \hspace{1cm} (5)

It is seen from Fig. 9b that the maximum PS is smaller and changes smoothly under the bending angle smaller than 52°. However, when the bending angle exceeds this angle, the curve slope becomes greater, which makes the PS change drastically. It is calculated by Eq. (5) that the
difference of the peak strains is about 0.085 with respect to the bending angles 43° and 64° of the first pass, which is surprisingly about 67.8% PS of 64°. Hence, the bending angle increment of the first pass has also a great effect on the rolled quality of the corrugated channels. The smaller the bending angle increment of the first pass, the smaller the maximum PS of the final rolled product, and thus, the defects like tearing and redundant deformation are not produced easily. Moreover, although the fitting curve slope is small after the bending angle larger than 60° and the PS changes smoothly, the corresponding maximum PS is larger. Therefore, the bending angle of the first pass is not recommended in this range.
4 Experimental verification

4.1 Experimental system

The roll forming machine of corrugated channels is mainly composed of roll stations, a support, inverter motors, and control boxes; see Fig. 10a. The multi-section contour of roll is designed according to the proposed RFT above, and the corresponding bending angles are conform to those of the first group in Table 4, which are also regarded as the simulation angles. The roll forming speed can be adjusted by the inverter motor and the frequency converter in the control box. The friction between the sheet and roll can be improved by oil lubrication. After the sheet metal is bitten into the forming passes and the final rolled product is performed by this machine, then the sleeve is spin-made for the industrial support; see Fig. 10b and c.

4.2 Validation and analysis

Additional to the process design, the quality of the final product is known to be highly sensitive to the unavoidable variations during the assembly, which can be solved by adjusting the roll gap and improving the lubrication conditions. It can be observed from Fig. 10b that although the surface of the corrugated channels is not smooth and presents a slight bow distortion, the depth of channel 3 is obviously larger than that of other ones. This indicates that the channel 3 has produced a large redundant plastic strain, which is consistent with the result from the simulation above. Moreover, to verify the simulation precision, the radial maximum depth of the channel 3 trough is measured from starting element 14,077 to ending element 14,229 as a quality control index of product; see Fig. 11. Meanwhile, to decrease the measuring error, three rolled forming data are collected along the forming direction in each of six passes. Then their average values are used to compare with the theoretical data, respectively.

In general, the measured values are smaller than both the simulation and theoretical data; see Table 5. This is mainly because the roll gap in experiment is adjusted greater than that in simulation or theoretical analysis, to avoid effectively the sheet tearing caused by the assembly error. Also, the simulation results are smaller than the theoretical, which is mainly caused by the springback and shrinkage of the materials in simulation. However, the maximum error between them is only 0.176 mm, which is less than 3% of the maximum theoretical data and is within the range of allowable error. On the other hand, this also demonstrates that the developed RFT of the corrugated channels is reasonable.

![Fig. 9](image-url) Relations between peak strain and two factors. a Friction coefficient, b bending angle of first pass

| Table 4 | Bending angle and increment of four groups |
|---------|------------------------------------------|
| Groups  | First | Second | Third | Fourth |
| θ(°)    | 43    | 75     | 90    | 50     |
| Δθ(°)   | 43    | 32     | 15    | 50     |

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Fig. 10 Experimental system and product. a Roll forming machine, b corrugated channels, c aluminum sleeve

(a) Roll forming machine
(b) Corrugated channels
(c) Aluminum sleeve

Fig. 11 Measuring radial depth of channel 3 trough

Table 5 Maximum radial depth of channel 3 trough (mm)

| Pass       | 4th  | 5th  | 6th  | 7th  | 8th  | 9th  |
|------------|------|------|------|------|------|------|
| Theoretical| 3.823| 5.438| 5.734| 5.5  | 5.5  | 5.5  |
| Simulated  | 3.816| 5.427| 5.728| 5.490| 5.492| 5.487|
| Measured   | 3.677| 5.289| 5.584| 5.362| 5.316| 5.380|
5 Conclusion

(1) To effectively avoid sheet tearing and improve the quality of the final rolled product, a symmetric roll forming technology is developed in view of the corrugated channels with thin wall, large number, and asymmetric channel width. And the rationality of the RFT is verified through the simulation and experiment, respectively.

(2) Even though both the contours of channels are rolled simultaneously, their maximum peak strains are also distinguished due to their different widths in roll forming of the corrugated channels. The maximum PS of the narrow channel is greater than that of the wide, which is on the right of the trough bending angle. And the closer to the middle channel, the more obvious this law. This also mainly causes the bow defect of the corrugated channels.

(3) The effects of three factors on the maximum PS of corrugated channels are investigated. Both the bending angle and friction coefficient are dominant factors, whereas the forming speed is not obvious. This can provide a reference for the control defects and the quality improvement of final rolled product.

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Yifan Wei: Simulation and collection of experiment data
Tuo Pan: Design experiment device and collection of experiment data
Jianchao Chen: Collection of experiment data

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