A Study of Cold Roll Forming Technology and Peak Strain Behavior of Asymmetric Corrugated Channels

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Research Article

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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 under the study 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 for two roll forming channels at the same time, even under the equal bending angles and the pressures of rolls, their maximum peak strains are also distinguished for their different channel widths. 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 dominant by the friction coefficient and bending angle of the first forming pass. This can provide a reference in the design of RFT and improving the quality of the final rolled corrugated channels.

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 stands. 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 and then is 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 and so on, see Table 1. Therefore, although the paper sleeve is now widely used for the support of aluminum coil, the aluminum one has a more extensive application prospect and promotion value, instead, see **Fig. 1**.

Despite the forming principle visual simplicity, since affected by the factors like sheet materials, slip and friction, the strain behavior of the materials during the bending process is extremely complicated. As the sheet metal moves through the rolls, the corrugated channels easily cause like defects tearing, hardening and edge wrinkles once the roll forming technology is designed unreasonably.

Table 1
Performance comparison between aluminum and paper sleeves (type: 505*20*100)

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

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 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 complex due to larger number, smaller interval and asymmetric width of their channels. And the mentioned above will make them tear because of the sheet metal contraction interfered by the multi-section contours of rolls.

Su [6] has optimized the bending angle distribution function of contour plate through analyzing the effects of the bending angle, sheet thickness and the 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 research on the RFT of corrugated channels is relatively few and mainly depends on the experiments. Thus, it inevitably causes low efficiency and high costs in this aspect. For this, 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 improving the quality 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. 2(a)**. Namely, the number of all the forming passes is divided into three sets, the middle channel 4 is first performed in the first set, then the channels 3 and 5 or 2 and 6 are simultaneously rolled into shape in turn in other two sets.

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 molding passes, see Table 2.

$\Phi = nW_1 h / W_2$ (1)

$\cos\theta_i = 1 + (1 - \cos\theta_0)[2(i/n)^3 - 3(i/n)^2]$ (2)

where Φ 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, respectively; θ_i is bending angle of roll; i is the forming pass order and θ_0 is the final bending angle of roll.

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

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

Sets	**1#**			**2#**			**3#**		
Passes	1st	2nd	3rd	4th	5th	6th	7th	8th	9th
(°)	43	75	90	43	75	90	43	75	90

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 materials used for simulation in this paper is aluminum sheet 6061-T6 with width of 76mm and thickness of 0.25mm, 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 800mm pre-cut sheet more than 3 passes (roll station distance 300mm) is hereby fed into the rolls. And the roll is set as the shell element S4R and discrete rigid body. Then, the assembly model of the corrugated channels is established in FE, see Fig. 3.

Table 3
Mechanical properties of Aluminum Alloy (6061-T6)

E **(Mpa)**	***μ***	**σ_s (Mpa)**	**σ_b (Mpa)**	**ρ ▯Kg/m3▯**
69000	0.33	275	355.8	2700

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 large or small, 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 product 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 is first set 0.1 between the sheet and roll. Then the time is set 28s in the STEP module according to the distance between the first and ninth passes about 2800mm. After the display dynamics algorithm is adopted, the sheet is fed into the rolls at a forming speed of 100mm/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 node 459 to the end 307. Thus, the sheet strain behavior can be described by corresponding node in roll forming of the corrugated channels.

It is seen from **Figs. 4** (a) and (b) that the channel 4 roll forming 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 asymmetry of the corrugated channels, the center lines between the roll contour and 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 peak, 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 for other four channels, the ones of the narrow channels 2 and 3 are significantly larger than those of the wide 5 and 6 even though both the channels 2 and 6 or 3 and 5 are rolled at the same time, see **Figs. 4 (c) 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 pressures, 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 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 roll forming process of the corrugated channels, a unit 17287 of this region is used for the subsequent work. This can simplify the research without loss of generality.

The stress history of this unit is relatively complex caused by the extrusion, stretching and shearing forces. It is seen from **Fig. 5(a)** that the whole process is roughly divided into three stages according to the RFT. The channel 4 is performed in the first stage, next is the channels 3 and 5 in the second, and the rest 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 unit still produces a certain stress. However, its maximum PS is lower than the yield limit stress of materials, hence only the pure elastic strain is produced, which disappears after the channel 4 is finally formed for without any roll pressures.

However, the unit stress increases abruptly from about 121 to 275MPa in the forming direction 1100mm. This indicates that the unit has entered the second stage and obviously, its stress law presents three cycles. In the first cycle, its maximum PS is about 321.9MPa in the forming direction 1252mm between the third and fourth passes. Whereas, the PS becomes small, instead and is only 194.9MPa at the contact point between the sheet and the fourth roll in the direction 1312mm, see **Fig. 6**. To demonstrated this issue, Bhattacharyya et al. [10] 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, it can also well be illustrated by similar force law of the cantilever beam, in which the beam stress changes with the distance from its end under a force.

When the unit 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 352MPa. This is mainly because the change of roll bending angle between these two passes is greater than that of others, which hence results in a large force exerted on the unit. With respect to the effect of bending angle, it will be further studied in Sect. 4. Surprisingly, although the unit 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 unit is still subject to three periodic stress under the roll forming of the channels 2 and 6. Since its PS does not exceed the yield limit of 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 has been done a lot based on the single channel roll forming to control the quality of the final rolled product [11, 12], however, the strain behavior of the corrugated channels is also distinguished from the single one 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 unit 17287, respectively.

3.1. Forming speed

Fig. 7(a) shows the strain behavior of the unit under four different forming speeds in three stages. The unit 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 and 200mm/s. This shows that the effect of the forming speed is smaller 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 [13]. 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 the sheet and the forming speed of the roll have no effect on the longitudinal strain of the side.

3.2. Friction coefficient

The corrugated channels roll forming is mainly dependent on the contraction and slippage of the sheet between the multi-section contour of roll and thus is affected by the friction, inevitably. For analyzing the effect of friction, the strain behavior of the unit 17287 is also used to simulate in roll forming under the friction coefficients 0.1 ~ 0.25.

It is seen from Fig. 7**(b)** that the larger the friction coefficient, the greater the unit PS. The difference of PS between the minimum and maximum friction coefficients is 0.035, which indicates the PS of the corrugated channels is significantly influenced by the friction. And a larger friction coefficient easily leads to the sheet tearing and thus affects the forming quality of the product. In order to better analyze the effect of friction, the peak strains of the final rolled corrugate channels are fitted under different friction coefficients, correspondingly, as shown in **Fig. 8(a)**.

A nonlinear relationship is presented in **Fig. 8(a)** between the unit PS and the friction coefficient. Under the friction coefficient less than 0.15, the unit PS increases gradually with the friction coefficient, of which range is smaller than 0.005. However, it increases drastically after the friction coefficient greater than 0.15. This indicates that the friction coefficient has a great effect on the quality of the corrugate channels within this scope. Unfortunately, the result from simulation is contradicted with the conclusion which is obtained based on the single contour roll forming by Bidabadi et al [14]. This is mainly because the RFT of the corrugated channels are more complex. Although the forming of their middle channel is similar to the single one, the forming of both sides are mainly dependent on the strip sliding between multi-section contour of the roll and thus, a greater friction is produced inevitably.

3.3. Bending angle

The bending angle is the most important parameter in roll forming process, which has a major effect on the quality of the formed product [15, 16]. However, in the current production stage, the traditional RFT still arbitrarily sets the bending angle of each pass to produce the cross-section shape of the desired product based on production experience.

With respect to the effect of bending angle θ on the PK of corrugated channels, here four groups of bending angles are first determined according to the formula 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.

Table 4
Bending angle and increment of four groups

Groups	First			Second			Third			Fourth		
$\theta(^{o})$	43	75	90	50	77	90	57	79	90	64	81	90
$\Delta\theta(^{o})$	43	32	15	50	27	13	57	22	11	64	17	9

As can be seen from Fig. 7**(c)**, although four groups of final bending angles are all 90°, the corresponding peak strains are significantly distinguished due to their different increments, instead. For the bending angles 43^{o} and 64^{o} of the first pass, respectively, the difference of their peak strains of the final rolled products is about 0.085, which is surprisingly about 67.8% of the PS of 64^{o}. Therefore, the bending angle increment of the first pass has 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 easily produced.

In order to further analyze the effect of bending angle of the first forming pass, the maximum peak strains of four group final rolled products are fitted, correspondingly. It is seen from **Fig. 8(b)** that the maximum PS is smaller and changes smoothly under the bending angle smaller than 52^{o}. However, when the bending angle changes between 52 ° and 60 °, the curve slope becomes greater, which makes the PS change drastically. Hence, the channel is prone to tearing in roll forming. Also the curve slope is small after the bending angle larger than 60° and the PS changes smoothly, whereas the corresponding maximum PS is bigger, thus 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. 9(a)**. 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 forming speed of roll 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.

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 **Figs. 9(b) and (c)** 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 simulation above. Moreover, to verify the simulation precision, the radial maximum depth of the channel 3 trough is measured as a quality control index of product, see Fig. 10. Meanwhile, to decrease the measuring error, three sets of data are collected along the forming direction, respectively. Then their average values are used to compare with the theoretical data.

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

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 of them is only 0.176mm, 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.

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 asymmetrical channel width. And the rationality of the RFT is verified through the simulation and experiment, respectively.

(2) Even though both the contour 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 distortion 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 improving the quality of final rolled product.

Declarations

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Authors Contributions

Chuntian Xu: Writing original draft, participating and guiding the programs.

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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Competing Interests

The authors have no conflict of interests to declare that are relevant to this article.

Availability of data and materials

Not applicable.

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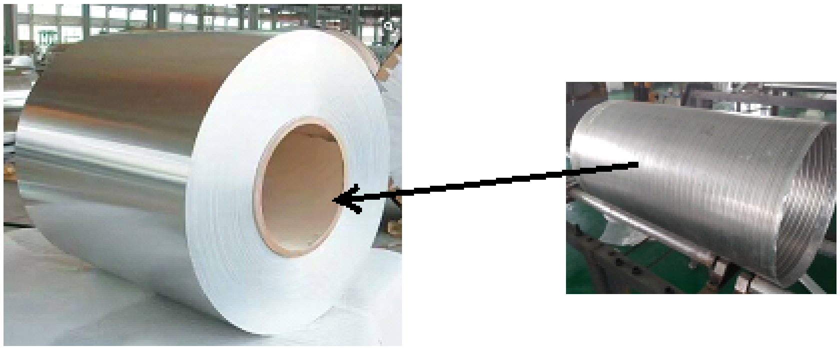
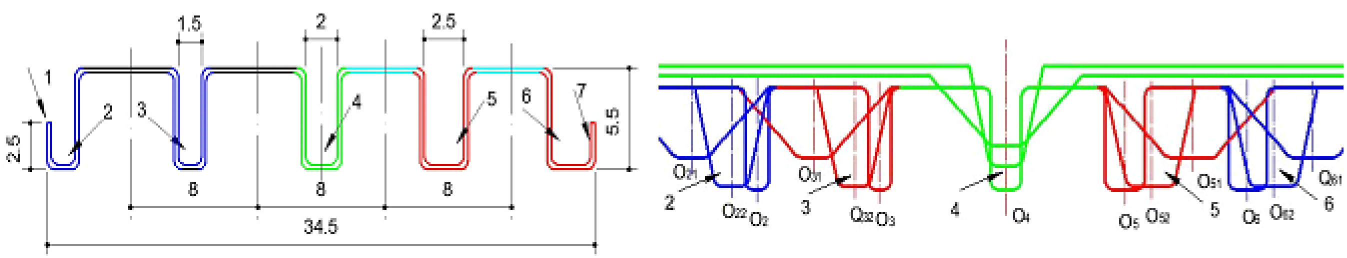
Figures



(a) Paper sleeve (b) Aluminum sleeve

Figure 1

Application of aluminum sleeve



(a) (b)

Figure 2

Geometric size and flower pattern of corrugated channels

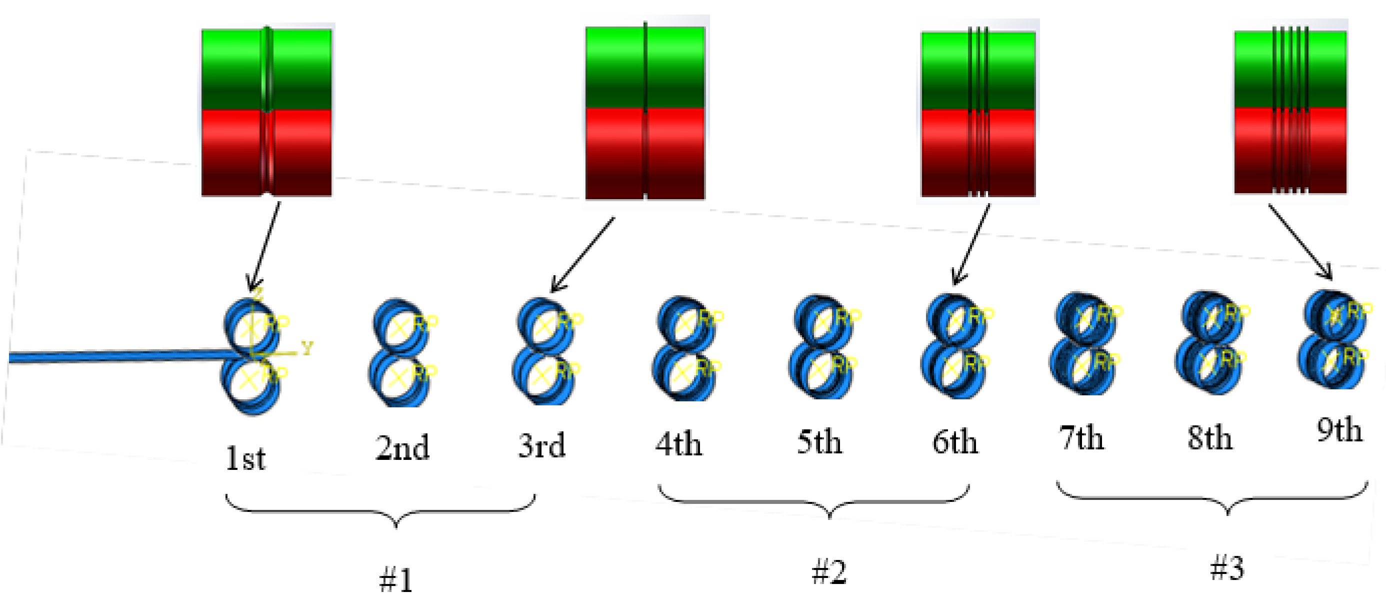


Figure 3

Assembly model of corrugated channels

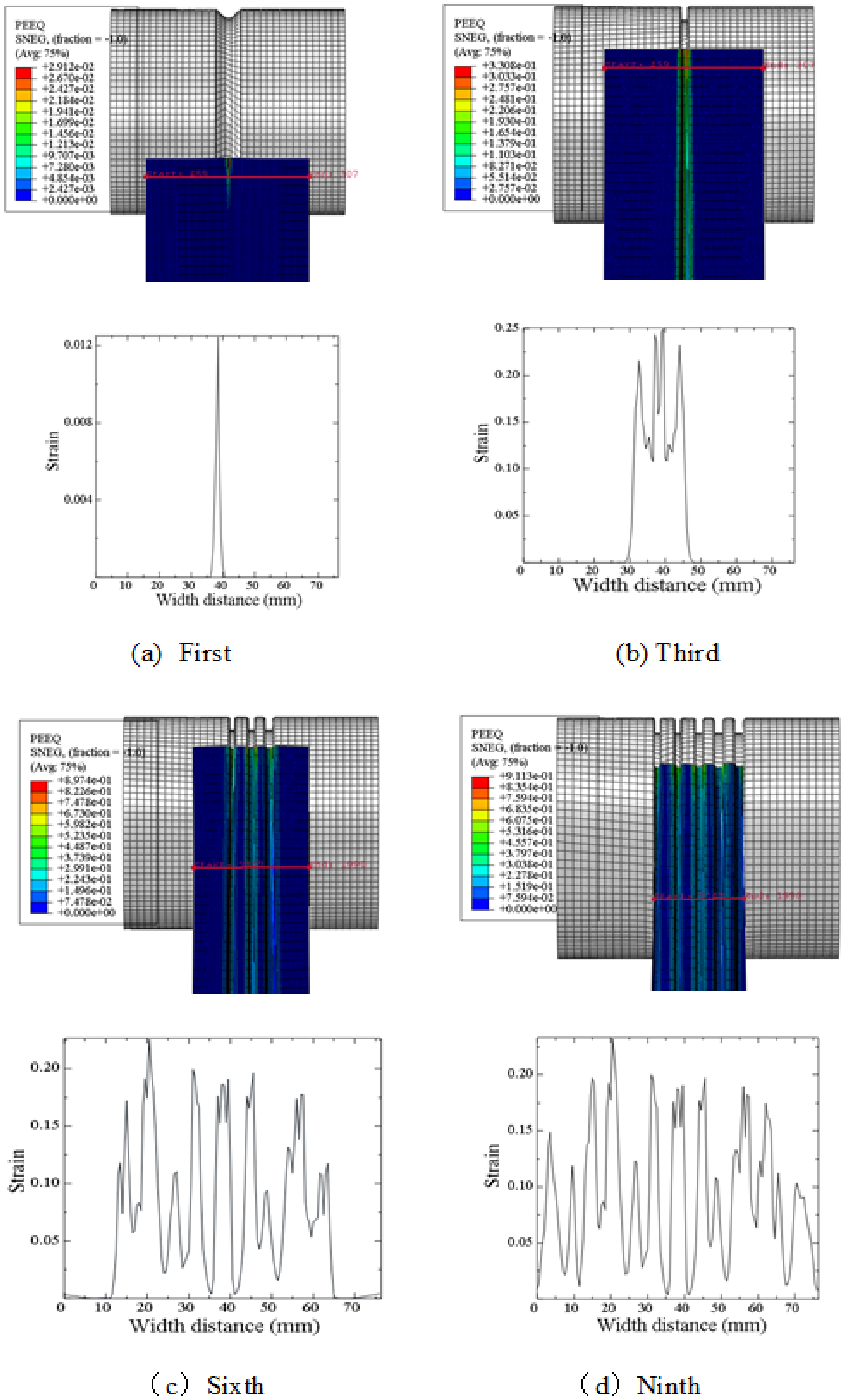


Figure 4

Sheet cloud maps and strain curves of four forming passes

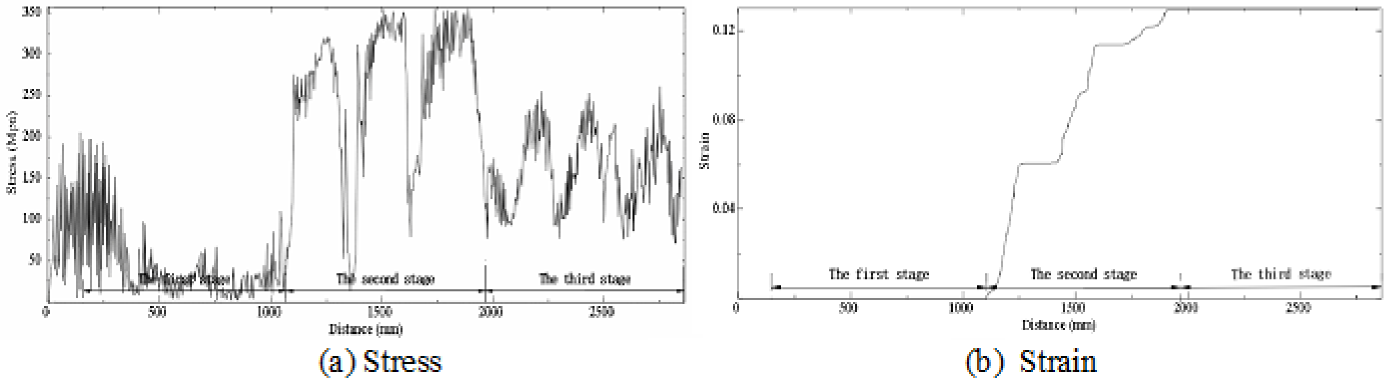


Figure 5

Stress-strain history of unit 17287

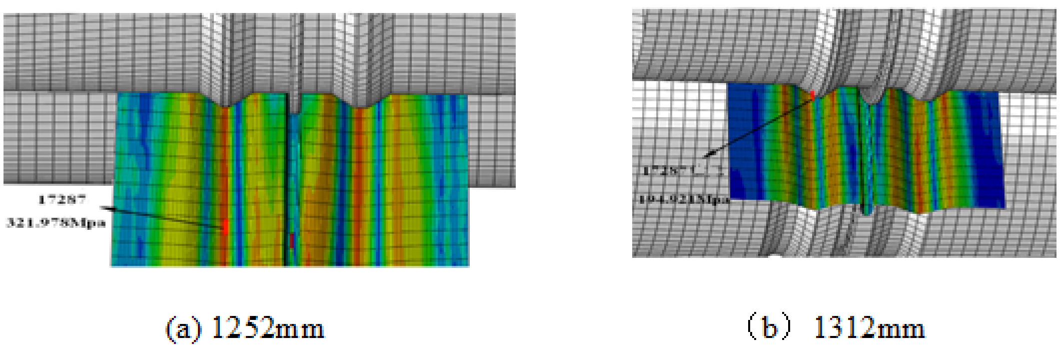


Figure 6

Peak stress of unit at different distance in forming direction

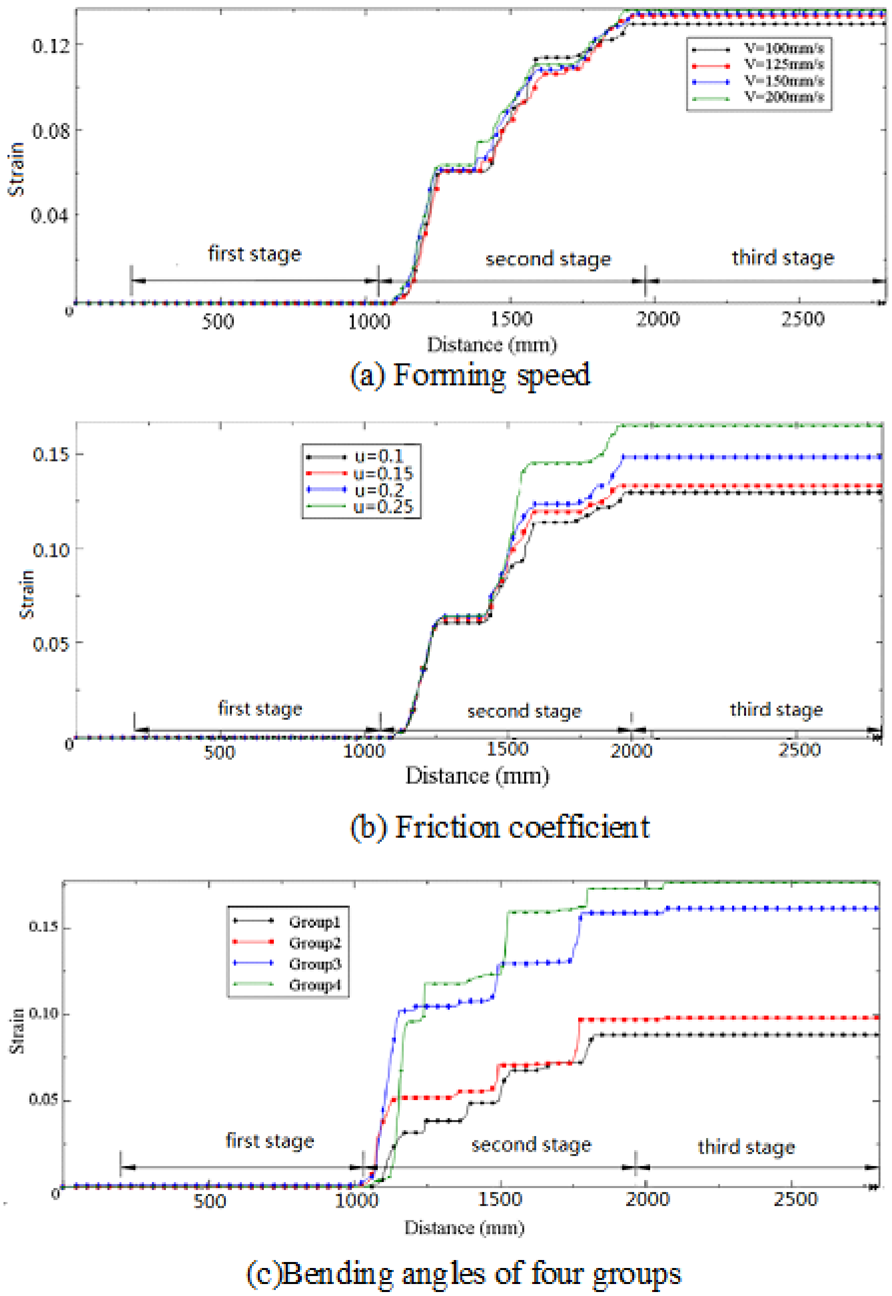
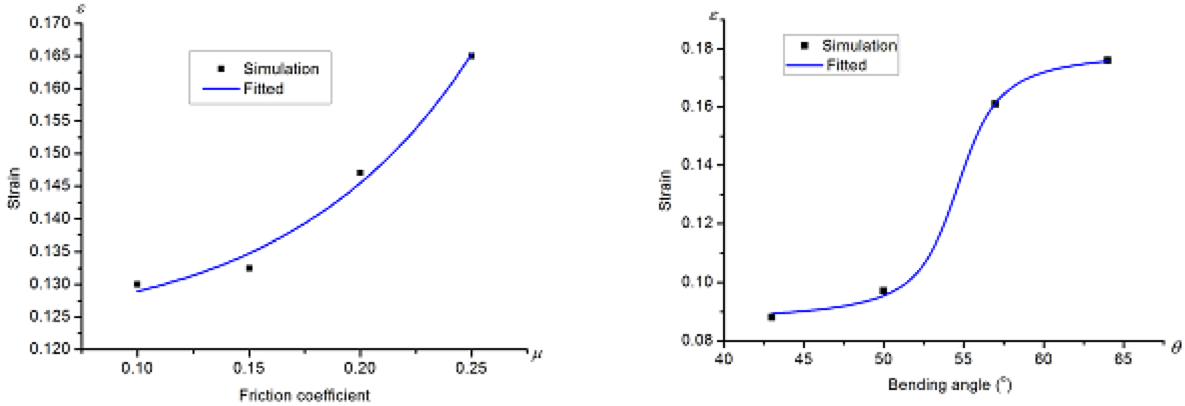


Figure 7

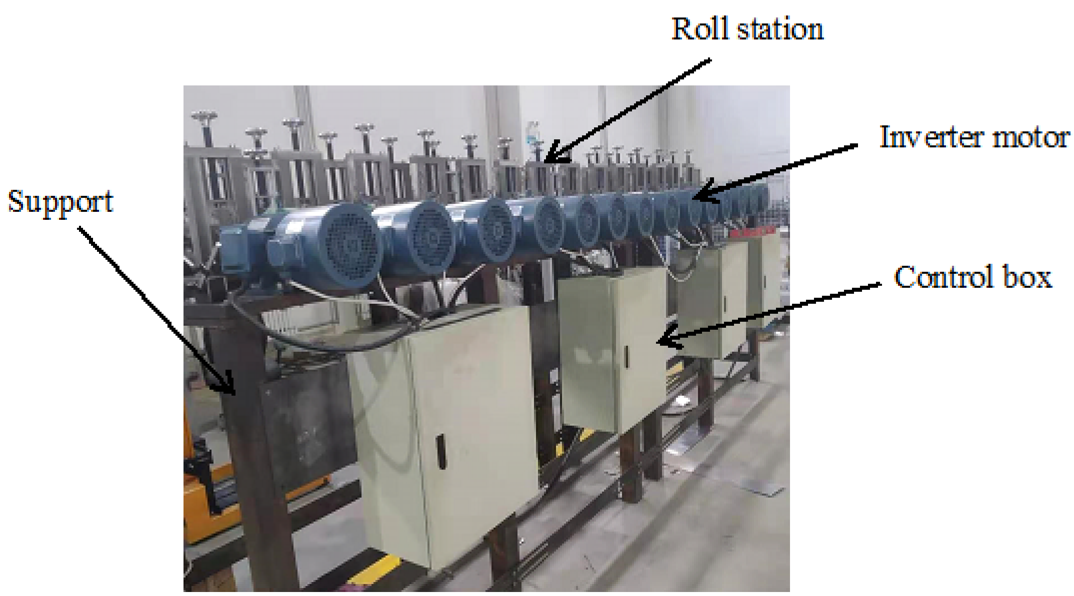
Strain behavior of unit 17287 under three factors in three stages



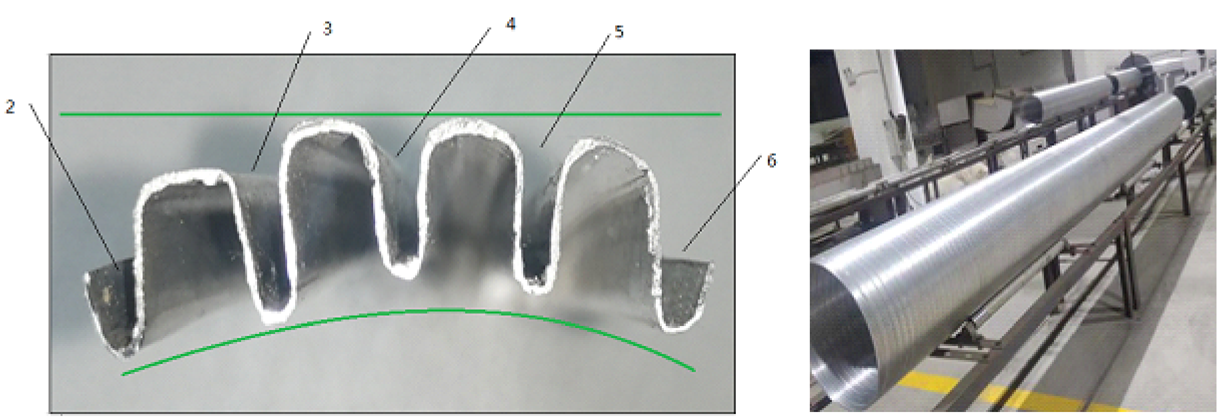
(a)Friction coefficient (b) Bending angle of first pass

Figure 8

Relations between peak strain and two factors



(a) Roll forming machine



(b) Corrugated channels (c) Aluminum sleeve

Figure 9

Experimental system and product

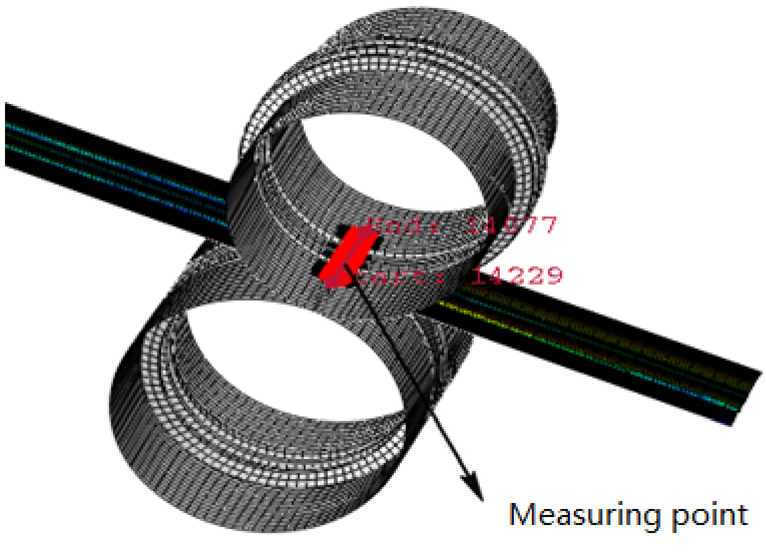


Figure 10

Measuring radial depth of channel 3 trough