Axial formation and cross-section distortion control for stretch bending based on batch simulations

Kaijun Lu¹, Jianxi Luo¹, Tianxia Zou¹, Dayong Li¹ and Yinghong Peng¹

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

Abstract. Stretch bending is a widely used to form long parts with a definite cross-section shape. The forming path is an effective way to eliminate the defects such as springback, distortion when the material and the die shape are determined. In this study, the stretch bending path is represented by a curve function of bending angle and stretch length. To simplify the path optimization problem, the path is represented by 4 parameters, including a newly introduced parameter of total stretch. Based on the batch simulation results, it is found that the axial springback and cross section distortion are primarily controlled by total stretch, bending angle and pre-stretch proportion. When the total stretch is determined, the different distribution schemes for pre-stretch, bending stretch and post-stretch in total stretch have a similar effect on forming quality except the schemes with extremely large proportions of pre-stretch. In most cases, with the total stretch length in growth, the axial springback decreases dramatically at first and then stays constant while the section distortion continues to rise, indicating that the optimal forming path is around the elbow point in the relationship curve of total stretch and springback angle. The optimal path is verified by experiments. It is shown that for a workpiece with determined material and die shape, the optimal path to minimize axial rebound and section distortion simultaneously does exit and the study provide an effective way to obtain it.

1. Introduction

The majority of current railroad car frames are composed of cold formed, extruded stainless steel tubes of different sections instead of unibody concepts, aiming at reducing the weight and the number of the components. The extrusions are manufactured by a series of cold forming operations, including sheet shearing, bending and stretch bending. The word “stretch” indicates that tensile force is applied to both ends of the extrusions during bending. Stretching is an effective way to avoid the cross section’s compression and reduce the axial springback by adjusting the stress distribution of the section to a more uniform state. Compared with a variety of other bending process (e.g. press bending, air bending and roll bending), stretch bending provides an efficient and low-cost method in the reduction of springback. Many studies have been conducted on the possible defects in stretch bending process including torsion, crack, cross sectional distortion and especially axial springback, according to analytical, numerical or experimental method.

Analytical method is based on simplified forming process, idealized material properties and pure bending hypothesis. Ueda and Ueno[1] firstly studied the effect of stretch on axial springback in the stretch bending of rectangular channels theoretically, indicating that the axial springback can be reduced by greater tension force, and the stretch before bending is less effective than the stretch after bending. Based on pure bending assumptions, A.A.El-Domiaty et al.[2] introduced a mathematical
model for stretch bending process to determine the effect of material properties on the process parameters including product geometry, residual stress and forming loads. Paulsen and Welo\cite{3} established analytical models to predict suck-in deformation and local post-buckling of rectangular hollow sections in stretch bending by using the energy method. Corona \cite{4} stressed the importance of appropriate tension force, indicating that higher tension reduced the axial springback while induced relatively large section distortion, and then presented an efficient formulation for cross sectional distortion prediction of thin-walled profiles. YU Cheng-long and LI Xiao-qi\cite{5} established a theoretical model to analyse the effect of pre-stretch force and post-stretch force on springback angle after forming in stretch bending process of L-section extrusions. Zhao et al.\cite{6} took the profile with arbitrary cross-section as the study object and obtained the universal analytical method to solve the springback problem of stretch bending in the loading method of pre-tension and bending moment, and verified the theoretical model with experimental and finite element numerical research on rectangular section and U-section profiles. On the basis of Jun Zhao’s work, Ruixue Zhai et al.\cite{7} extended the study to the loading method of pre-bending and tension, which is far more sophisticated than the loading method of pre-tension and bending, indicating that high tension and small bending radius can prevent rebounding significantly.

Compared with the analytical method, the finite element method provides a convenient way to deal with the workpiece with complex axial curve and complex cross-section shape. Hopperstad et al.\cite{8} studied the effect of different yield criterion on local deformations predicted in numerical simulation of stretch bending by using the software LS-DYNA3D. Hopperstad et al.\cite{9} assigned the material parameters randomly to analyze the reliability of the stretch bending process for U-sectional aluminum extrusions by using LS-DYNA3D. J.E. Miller and S. Kyriakide \cite{10} established 3-D finite element model to replace efficient 2-D model in which all applied loads and the cross section shape were assumed to be uniform along the axis, and studied the 3-D features problems such as springback and distortion along the axis based on 3-D model. Lasse Bjørkhaug and Torgeir Welo \cite{11} found that the cross section distortion is over-predicted by isotropic model, and improved the accuracy of finite element model by using the anisotropic Barlet96 yield model. YU Zhong-qi and LIN Zhong-qin \cite{12} studied the effect of processing parameters on the dimension precision of the U-shaped aluminum profile by using Dynaform, indicating that the section distortion decreases with the increase of the side pressure, whereas the axial springback increases, and both of the section distortion and axial springback decrease with the increase of the tension force. Y. Okudea et al.\cite{13} simulated the stretch bending of various channel section extrusions with laminated elastic mandrel inside by using LS-DYNA3D, proving effectiveness of the mandrel in preventing the undesirable cross section distortion. Tianjiao Liu et al.\cite{14} simulated the displacement controlled stretch bending of the 2099-T83 and 2196-T8511 Al-Li alloys extrusions by using Abaqus, indicating that the springback decreased significantly with the increase of post-stretch or pre-stretch. Chun-guo Liu et al.\cite{15} simulated the springback behavior of aluminum hollow profile under five levels of post-stretching elongations, indicating that high post-stretching elongation leads to small axial springback but large spatial twist and cross section distortion. Zhengwei GU et al.\cite{16} simulated the stretch bending of a L-section aluminum extrusion by using Abaqus and quantified the effect of die fittingness on horizontal plate sagging distortion.

With analytical and simulation methods, the effect of various forming parameters on quality has been explored in depth, improving the accuracy of forming results prediction and the control ability of forming quality. Arild H. Clausen et al.\cite{17} studied the effect of workpiece geometry and forming path on section distortion, indicating that the axial springback is primarily controlled by the tension force and the strain hardening exponent of the material while the cross-section distortion is primarily controlled by the workpiece geometry and tension force. By applying six forming procedures with different tension sequence into stretch bending of a car bumper numerically and experimentally, Arild H. Clausen et al.\cite{18} studied the effect of forming path on the section distortion and axial springback. J.E. Miller et al.\cite{19} constructed a custom bend-stretch-pressure forming facility to realize flexible control of forming path. Based on the experiments carried on the facility, the bend-stretch-pressure forming process is simplified to a 2D model, in which the cross-section shape and applied loads are assumed uniform along the axis. Based on the simplified 2D model, J.E. Miller et al.\cite{20} studied the
influence of forming process parameters on forming quality, indicating that the section distortion is primarily controlled by the tensile force and geometry while the axial springback is primarily controlled by tensile force and strain hardening exponent coefficient. Arild H. Clausen et al. [21] used factorial analysis in the planning of the experimental program and result interpretation to study the influence of the alloy, die radius and specimen wall thickness on response parameters such as die force, sagging and springback, indicating that the die force and springback is primarily controlled by alloy while the geometric parameters have the largest influence on the sagging behavior.

Previous studies have shown that the forming quality of stretch bending is primarily controlled by material properties, workpiece geometry and loading path. Compared with other means such as mold shape modification, material replacement or workpiece shape modification, path optimization is the most efficient and low-cost way to improve the forming quality.

In the present work, firstly, the finite element model is verified by the stretch bending experiment and a massive amount of data is obtained by batch simulation approach. Secondly, two new variables named distribution ratio and total stretch length are introduced to describe forming process, replacing various factors used in previous studies such as pre-stretch, bend stretch and post-stretch, and the relationship between forming path and forming quality is greatly simplified. Thirdly, the influence of forming path on forming quality is discussed. Finally, a series of experiments are carried out to confirm the conclusions drawn from analysis.

2. Stretch bending process

A typical stretch bending facility consists of four parts, as shown in Fig1: a mould is fixed on the work table, two arms for bending the workpiece into certain curvature, two tension cylinders for applying axial stretch while bending and two carriage for loading and unloading workpieces of different lengths in the appropriate positions. The forming process is usually divided into three steps: loading, forming and unloading. Firstly, the mold is installed on the work table, then two tension cylinders stretch out and two carriages are moved to appropriate positions to fix the workpiece at its ends by jaws. Secondly, the jaws moves along desired trajectories which is determined by the rotation of arms and the motion of the tension cylinders, affixing the workpiece to the mold and elongating it gradually. Thirdly, open jaws to release stress, then move the tension cylinders to the desired position for unloading.

![Fig 1. Schematic diagram of a typical stretch bending facility.](image)

2.1. Motion structure of the machine and the forming path

Because the stretch bending machine is structural symmetry, analysis of forming process is performed on half of the structure. The motion structure consists of three parts: arm, carriage and tension cylinder, and their locations jointly determine the location of the jaw, which is also the location of one end of the workpiece, as shown in Fig 2. In the loading step, the tension cylinder stays still, while the arm is rotated to a certain angle to make the workpiece tangent to the die profile, and the carriage is moved to the appropriate location to load the workpiece with different lengths smoothly. In the forming step, the arm is rotated to mould the workpiece axis into the desired contour while the tension cylinder is drawn back to stretch the workpiece along its axis. In the unloading step, the jaw on the end of the tension cylinder is opened to release the product.
All axial profile outlines of the workpieces are smooth convex curves, which can be described as continuously derivable functions and can be divided into several straight lines and arcs. Fig 3 shows typical axial profile outlines of a workpiece. The target product is composed of four segments including two straight lines (S2 and S4) and two arcs (S1 and S3). Compared with the target product, the actual product is longer on the two ends. The extra linear segments of actual product are LS3 and RS4, which are used for clamping during forming process as circled in Fig 3 and will be cut off after forming.

The deformation of the workpiece axis during the stretch bending process can be divided into the transverse bending effect and the axial stretching effect, which can be represented by the bending angle and stretch length respectively. Fig 4 shows a new representation method of forming process. Each point in the coordinate system represents a deformation state, including the bending angle and stretch length, and it is obvious that the initial state is at the origin (0°, 0mm). The forming paths are represented by the curves connecting the initial point and the destination point, and the number of possible forming paths is obviously infinite. To simplify analysis, a variety of forming paths are standardized to polylines composed of three linear segments, as the standard forming process can be divided into three steps including pre-stretch, stretch bending and post-stretch. The workpiece can be stretched during the forming process while it is bent only in the stretch bending step. Consequently, the first and third linear segments of a standard forming path are vertical while the second segment is an oblique line, as shown in Fig 4.
Therefore, the forming path problem consists of two crucial and critical parts. The first one is the final deformation state of the workpiece before rebound, which can be represented by the location of the destination point. In general, the springback angle is relatively small with a proper forming process, usually at 5% of the bending angle or lower. Accordingly, the target angle of the target product can be a suitable substitute for the bending angle when the axial rebound is ignored. The second critical part is the forming path connecting the initial point and destination point, which can be represented by three remaining variables including pre-stretch, bend stretch and post-stretch.

2.2. Processed profile

The product for illustration is a long rail with hat cross section which is made of stainless steel. The axis of the workpiece consists of three segments including one arc with angle 4.33° and two straight lines on two ends, as shown in Fig 5.

The purpose of the stretch bending is to form the axis of a long rod into the shape specified while keeping its cross section undeformed as far as possible. Consequently, the forming quality of stretch bending consists of the axial deformation and the cross sectional distortion, which are evaluated by $\theta_{AS}$, $h$ and $\theta_{e}$, as shown in Fig 6. $\theta_{AS}$ is the axial deformation angle after springback, and the difference between bending angle (or forming angle) and $\theta_{AS}$ is the springback angle. The cross section along the axis is not uniform anymore and the max deformation occurs on the arc segments of the axial curve. Meanwhile, the deformation of brim region is more server than other region in the cross section. Accordingly, the height from brim region to crown region and the angle between two hat edges are suitable to represent the distortion of the hat section.
3. Finite element simulation

3.1. FE modeling
A finite element model of the stretch bending process is developed by using ABAQUS/Standard software, as shown in Fig 7.

The material of the present hat-shaped workpiece is SUS-301 stainless steel and its true stress-true strain curve is presented in Fig 8. The workpiece shown in Fig 7 is divided into three layers of eight-node linear brick element with reduced integration (C3D8R). After a series of mesh sensitivity check, the element sizes of 5mm, 2mm, 0.8mm for longitudinal direction, slight deformation region and corner region respectively. The blank model has 177896 nodes and 131400 elements. Mold blocks are represented as discrete rigid surfaces and discretized by using R3D4 elements. The Coulomb friction model is assumed and the friction coefficient between the workpiece and mold blocks is set as 0.1.
During the stretch bending process, the mold stays still while two jaws clamp the two ends of the profile and move in designed trajectories. Accordingly, the constraints between the ends of workpiece and two jaws are set as “tie”. The trajectories are determined using the following steps, as shown in Fig 9: Firstly several dispersed featured points are selected from forming path curve to determine the total length and bending angle of the workpiece in different deform states. Secondly, the position of the jaw which is associated with the end of the workpiece is determined by the deform state of the workpiece. Thirdly, the trajectory of jaw is plotted by connecting amounts of locations of jaws in different deform states.

3.2. Experimental verification
The stretch-bending experiments are carried on the equipment of Cyril bath V-50, as shown in Fig. 10. The experimental results of different forming paths agree well with the numerical results and some results are shown in Table 1.

![Fig 9. Three steps to obtain the trajectory of jaw.](image)

![Fig 10. The experimental machine.](image)

| Number | Bend angle (°) | Pre-stretch (mm) | Bend stretch (mm) | Post-stretch (mm) | Calculated forming angle (°) | Measured forming angle (°) |
|--------|----------------|------------------|-------------------|------------------|-----------------------------|----------------------------|
| 1      | 4.4            | 0                | 5                 | 5                | 2.43                        | 2.35                       |
| 2      | 4.4            | 0                | 6.25              | 6.25             | 3.71                        | 3.55                       |
| 3      | 4.4            | 0                | 7.5               | 7.5              | 4.25                        | 4.2                        |
| 4      | 4.4            | 0                | 10                | 10               | 4.25                        | 4.25                       |
| 5      | 4.4            | 20               | 0                 | 0                | 0.5                         | 0.3                        |

4. Influence of forming path on formation quality
The forming path is a curve connecting the initial point and destination point in the coordinate of bending angle and stretch length, as shown in Fig 11.
Each point in the schematic is not only the deformation state of workpiece describing its elongation and bending degree, but also represents the strain distribution of the workpiece. The curve connecting all nodes is the forming path which describes the deformation history of the workpiece. The final strain distribution of the workpiece is determined by the location of the destination point while the final stress distribution of the workpiece can be altered by changing the forming path which connects the initial point and the destination point. In the following sections, the influence of the forming parameters on the forming quality is discussed in two aspects: one is the final deformation state of the workpiece which is represented by the bending angle and total stretch, and the other one is the forming path connecting the initial and the final deformation state which is represented by the stretch ratio.

4.1. Influence of stretch distribution

As mentioned earlier, there are infinite forming path curve connecting the initial point and the destination point. To simplify the analysis, 15 forming paths of different stretch schemes are simulated as shown in Fig 12.

Comparing forming results of 15 distribution schemes in Fig 12, all schemes are similar in forming quality except scheme 1 and scheme 2. Fig 13-15. shows the forming results of 15 schemes, whose bending angles are all 12° and total lengths range from 20mm to 200mm.
The particularity of scheme 1 and 2 is mainly caused by the unevenly distributed stress in the workpiece. The bending throughout the forming process causes the reverse loading of inner layers continuously. Without continuous stretch, the inner layers will be compressed and the stress in inner layers will decrease. Compared with the other schemes, scheme 1 and 2 stretch the workpiece little in the stretch bending step and post-stretch step, causing the unbalance of the stress between the inner and outer layers of the workpiece.

4.2. Influence of total stretch and bending angle

As stated above, the forming results of different forming paths are similar except with small stretch bending and post-stretch. Accordingly, the result of scheme 8 can be select as an example to study the influence of total stretch and bending angle on forming qualities.

Fig. 16 shows the influence of total stretch and bending angle on forming angle, indicating that with the increase of the total stretch, the springback reduces dramatically at first and then tends to be stable. When connecting all elbow points of different bending angles, the fitting is almost linear as shown in Fig 16. According to the linear relationship, the elbow point for an arbitrary bending angle can be easily obtained. Taking the product for instance, its bending angle is about 4.3° and the total stretch of the elbow point should be about 17mm according to the proportional relationship.

The springback angle, which is stable with the increase of the total stretch, is linearly proportional to the bending angle, as shown in Fig 17. According to the proportional relationship, the bending angle for an arbitrary target angle (e.g. the angle after springback) can be easily obtained. Taking the product for instance, its target angle is 4.22° and the bending angle should be 4.27° according to the proportional relationship.
Fig 17. Relationship between bending angle and springback angle.

Fig 18 and Fig 19 shows the influence of total stretch and bending angle on section distortion, indicating that with the increase of the total stretch, the section distortion fluctuates irregularly at first and then increases continuously.

**Figure 18.** Influence of total stretch on section distortion parameter $\theta$.  
**Figure 19.** Influence of total stretch on section distortion parameter $h$.

It is obvious that the increase of total stretch in the axial direction causes more severe section distortion. The fluctuation in the initial stage of the curve is caused by the detachment between workpiece and mold. When the workpiece is bent slightly, the distance between the two ends of workpiece will be smaller than the original length, and the axis of the workpiece will be more likely to be formed into a deflection curve, rather than the target axial curve of the mold, as shown in Fig 20.

| step | FEM of detachment |
|------|-------------------|
| 1    | ![FEM 1](image1) |
| 2    | ![FEM 2](image2) |
| 3    | ![FEM 3](image3) |
| 4    | ![FEM 4](image4) |
| 5    | ![FEM 5](image5) |

**Fig 20.** Detachment caused by slight bend.

4.3. **Optimum forming path**

The optimum path destination end is obviously around the elbow point. With a determined path end, the forming path, which is described by the stretch distribution, has little influence on forming quality except for some extreme cases with large ratio of pre-stretch. Accordingly, all rest paths are recommended for forming.
5. Experimental verification
A series of experiments are carried out on a Cyril bath V-50 stretch bending machine to verify the conclusions above. The forming angle is measured by inclinometer while the distortion of the section is identified by visual inspection assisted with a square ruler. The experimental results of different forming paths agree well with FEM model, as follows:

1) The results of experiments 1-4 are shown in Fig 21. With the increase of the total stretch, the forming angle increases dramatically at first and then tends to be stable while the section distortion increases continuously and obvious distortion is observed in experiment 4.

![Fig 21. Influence of total stretch.](image)

| Exp num | 1 | 2 | 3 | 4 |
|---------|---|---|---|---|
| Total stretch/mm | 10 | 12.5 | 15 | 20 |
| Forming angle | 2.28 | 3.06 | 4.25 | 4.35 |

2) Fig 22 shows that the distribution of stretch does not have significant effect on forming angle except when the bend stretch and post-stretch are too small. The springback of axial angle increase dramatically when the bend stretch and post-stretch are extremely small in experiment 9.

![Fig 22. Influence of stretch distribution.](image)

| Exp num | 9 | 12 | 11 | 10 | 4 |
|---------|---|----|---|---|---|
| Pre-stretch/mm | 20 | 5 | 10 | 15 | 0 |
| Bend stretch/mm | 0 | 7.5 | 5 | 2.5 | 10 |
| Post-stretch/mm | 0 | 7.5 | 5 | 2.5 | 10 |

3) It is shown that exp4 and exp10-12 are all appropriate forming path for the illustrated product, which is small in axial springback and section distortion.
6. Conclusion

In this work, the stretch bending process of a rail made of SUS301 stainless steel with hat shape section is studied by experiment, finite element simulation, and the following conclusion can be drawn.

1) The finite element model agrees well with the experiment results.
2) With the increase of the total stretch, the springback of the axial reduces dramatically at first and then tends to be stable while the distortion of the section increases constantly.
3) The forming path (e.g. stretch distribution) hardly affect the forming quality with a few exceptions, in which the ratio of bend stretch or post stretch is large.
4) The optimal forming path can be obtained accurately and effectively by batch simulation and subsequent analysis.

[1] Ueda M, Ueno K, Kobayashi M. A study of springback in the stretch bending of channels[J]. Journal of Mechanical Working Technology, 1981, 5(3-4): 163-179.
[2] El-Domiaty A A, Shabara M A N, Al-Ansary M D. Determination of stretch-bendability of sheet-metals[J]. International Journal of Machine Tools and Manufacture, 1996, 36(5): 635-650.
[3] Paulsen F, Welo T. A design method for prediction of dimensions of rectangular hollow sections formed in stretch bending[J]. Journal of Materials Processing Technology, 2002, 128(1-3): 48-66.
[4] Corona E. A simple analysis for bend-stretch forming of aluminum extrusions[J]. International Journal of Mechanical Sciences, 2004, 46(3): 433-448.
[5] YU C, LI X. Theoretical analysis on springback of L-section extrusion in rotary stretch bending process[J]. Transactions of Nonferrous Metals Society of China, 2011, 21(12): 2705-2710.
[6] Zhao J, Zhai R, Qian Z, et al. A study on springback of profile plane stretch–bending in the loading method of pretension and moment[J]. International Journal of Mechanical Sciences, 2013, 75: 45-54.
[7] Zhai R, Ding X, Yu S, et al. Stretch bending and springback of profile in the loading method of prebending and tension[J]. International Journal of Mechanical Sciences, 2018, 144: 746-764.
[8] Hopperstad O S, Berstad T, lIstand H, et al. Effects of the yield criterion on local deformations in numerical simulation of profile forming[J]. Journal of materials processing technology, 1998, 80: 551-555.
[9] Hopperstad O S, Leira B J, Remseth S, et al. Reliability-based analysis of a stretch-bending process for aluminium extrusions[J]. Computers & structures, 1999, 71(1): 63-75.
[10] Miller J E, Kyriakides S. Three-dimensional effects of the bend–stretch forming of aluminum tubes[J]. International journal of mechanical sciences, 2003, 45(1): 115-140.
[11] Bjørkhaug L, Welo T. Local Calibration of Aluminium Profiles in Rotary Stretch Bending—Anisotropy Effects[C]//AIP Conference Proceedings. American Institute of Physics, 2004, 712(1): 749-754.
[12] Yu Z Q, Lin Z Q. Numerical analysis of dimension precision of U-shaped aluminium profile rotary stretch bending[J]. Transactions of Nonferrous Metals Society of China, 2007, 17(3): 581-585.
[13] Okude Y, Yoshihara S, Saito A, et al. Bending deformation behavior of Aluminium extruded various sections with laminated elastic mandrel on draw bending[J]. Materials Today: Proceedings, 2015, 2(10): 4802-4811.
[14] Liu T, Wang Y, Wu J, et al. Springback analysis of Z & T-section 2196-T8511 and 2099-T83 Al–Li alloys extrusions in displacement controlled cold stretch bending[J]. Journal of Materials Processing Technology, 2015, 225: 295-309.
[15] Liu C, Zhang X, Wu X, et al. Optimization of post-stretching elongation in stretch bending of aluminum hollow profile[J]. The International Journal of Advanced Manufacturing Technology, 2016, 82(9-12): 1737-1746.
[16] Gu Z, Lv M, Li X, et al. Stretch bending defects control of L-section aluminum components with variable curvatures[J]. The International Journal of Advanced Manufacturing Technology, 2016, 85(5-8): 1053-1061.
[17] Clausen A H, Hopperstad O S, Langseth M. Stretch bending of aluminium extrusions for car bumpers[J]. Journal of Materials Processing Technology, 2000, 102(1-3): 241-248.
[18] Clausen A H, Hopperstad O S, Langseth M. Sensitivity of model parameters in stretch bending of aluminium extrusions[J]. International Journal of Mechanical Sciences, 2001, 43(2): 427-453.
[19] Miller J E, Kyriakides S, Bastard A H. On bend-stretch forming of aluminum extruded tubes—I: experiments[J]. International Journal of Mechanical Sciences, 2001, 43(5): 1283-1317.
[20] Miller J E, Kyriakides S, Corona E. On bend-stretch forming of aluminum extruded tubes—II: analysis[J]. International Journal of Mechanical Sciences, 2001, 43(5): 1319-1338.
[21] Clausen A H, Hopperstad O S, Langseth M. Stretch bending of aluminum extrusions: effect of geometry and alloy[J]. Journal of engineering mechanics, 1999, 125(4): 392-400.

Acknowledgments
The authors would like to acknowledge the support of National Science Foundation of China (Grant No.U1860110). And the authors would like to thank CRRC Changchun Railway Vehicles Co, Ltd. for providing manufacturing assistance.