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FEM simulation of flexible roll forming based on different material models①

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Abstract

Flexible roll forming is a new roll forming process that produces parts with variable cross sections. This forming process is proposed to meet the demand of weight reduction of automobile industry. In order to study the mechanisms and material flow rules in this new forming process, the finite element mothod (FEM) model of a nine-step flexible roll forming of an ultra-high-strength steel bumper is established based on deep understanding and reasonable simplification of the process. Given that the material model is an important factor that influences the simulation accuracy, three material models which consist of different yield criteria and hardening models are adopted in the FEM models. Sheet thickness and springback amount calculated with three material models are studied comparatively. According to sheet thickness reduction and springback amounts, it is found that the MKi (Mises yield criterion and kinematic hardening law) model's result is larger than MI (Mises yield criterion and isotropic hardening law) model and HI (Hill's yield criterion and isotropic hardening law) model. Therefore, it is concluded that material models do have influences on the flexible roll forming simulation and need to be determined carefully.

Key words: flexible roll forming, finite element mothod (FEM) modeling, material model, ultra-high-strength steel

0 Introduction

The use of roll-formed products in automotive, furniture, buildings, etc. increases every year due to low part-production cost and complicated cross-sections that can be produced[1]. In roll-forming processes, metal sheets progressively deformed into products with required cross-sectional profiles by a series of rollers installed at the tandems along the longitudinal direction[2]. Usually roll formed sections have a constant longitudinal cross-section, while certain fields like the automobile industry have shown a demand on profiles with variable cross-sections in order to meet the demand of weight reduction. The concept of flexible roll forming that could produce panels with variable cross-sections in the longitudinal direction was brought up in Ref. [3].

In order to provide scientific knowledge of roll forming and replace the trial and error method, a number of numerical simulations have been conducted[2,4-6]. Due to the complicated deformation of the roll forming process, most finite element (FE) models described in the literature are based on two approaches. The sheet goes forward under the action of the friction force from the rotating rollers[3,7], which is exactly the same as the real forming process. The sheet is pulled longitudinally from the leading edge through the roller gaps[8,9], which is an approximation of the relative motion of the rollers and the sheet. The results of both approaches in terms of strains and geometrical parameters are mostly satisfactory. By finite element mothod (FEM) simulation of the flexible roll forming, only a few studies are conducted, and the cross sections of the formed parts are simple U-sections. Gülçeken et al.[10] established a three dimensional flexible roll forming FEM model with the commercial roll forming finite element analysis (FEA) software (COPRA FEA RF), by which the feasibility of flexible roll forming process was verified. Piao[11] performed the FEM simulation of the flexible roll forming of a variable U-section sheet, by which characteristics of horizontal and vertical rollers are analyzed.

Roll forming is a complicated forming process. Multiple times of bending and reverse bending take

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place in the lateral direction, while tension and compression appear repeatedly in the longitudinal direction. As to the flexible roll forming, since the bend lines are always not parallel to the longitudinal axis, the state of strain and stress is more complex. The non-uniformity of the deformation in flexible roll forming will severely affect the dimensional accuracy of the product, and some forming defects such as edge wave, longitudinal bending, and twisting are prone to happen. Therefore, the study of the forming mechanisms of flexible roll forming is necessary to understand these phenomena which were paid little attention to in the previous researches.

The objective of this study is to establish an FEM model of a nine-step flexible roll forming process, which realizes translation and rotation of the rollers and feed of the sheet effectively. Different yield criteria and hardening models are used in the FEM analysis to study the influences of the material models on the deformation and springback. The results of this study will be useful in further improvement of the simulation accuracy.

1 FEM modeling of the flexible roll forming

1.1 Description of the forming problem

FEM modeling is carried out on the flexible roll forming of an automobile bumper. The dimensions of the sheet blank are shown in Fig. 1 (Half of the blank is shown because of symmetry). The cross sections of the objective shape are shown in Fig. 2. Nine pairs of rollers are adopted to form this structure. The inner section of the part is roll formed in the first five roller stands and the outer section is formed in the next four roller stands.

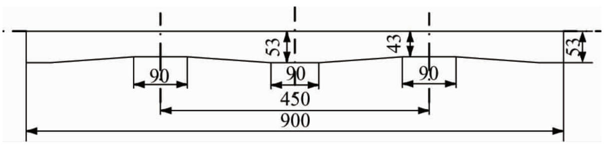
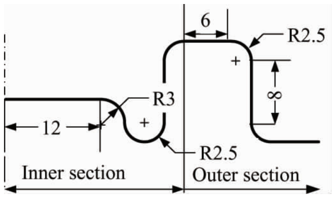
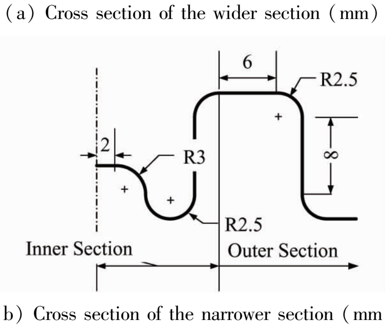


Fig. 1 Dimensions of the blank sheet (mm)



(a) Cross section of the wider section (mm)



(b) Cross section of the narrower section (mm)

Fig. 2 Dimensions of the variable cross sections

1.2 Establishment of the FEM model

The sheet thickness is 1mm. Since thickness is significantly smaller than the other dimensions and the stresses in the thickness direction are negligible, the specimen is modeled with 3D shell element: S4R. The rollers are modeled with rigid shell element: R3D4. Since the roller radius is rather small, the smallest length of the sheet element is 0.8 mm in order to avoid rigid body penetrations. The total number of the sheet elements is 25 040.

The sheet material is ultra-high-strength steel that may reduce the weight of automobiles while possessing high strength. The Young's modulus is 210 GPa, and the initial yield strength is 1 200 MPa. The hardening coefficient k is 1 500 MPa, and the hardening exponent n is 0.2. In order to study the influences of different material models on the simulation of flexible roll forming, three material models are adopted. The first consists of Mises yield criterion and isotropic hardening law (MI), the second consists of Hill's yield criterion and isotropic hardening law (HI), and the third consists of Mises yield criterion and kinematic hardening law (MKi).

The expressions of three material models for the shell elements are as follows.

MI:

$$f(\sigma_{ij}) = \sigma_{xx}^2 - \sigma_{xx}\sigma_{yy} + \sigma_{yy}^2 + 3\sigma_{xy}^2 - \bar{\sigma}^2 \tag{1}$$

HI:

The expression of Hill 48 yield criterion is

$$f(\sigma_{ij}) = (G+H)\sigma_{xx}^2 - 2H\sigma_{xx}\sigma_{yy} + (H+F)\sigma_{yy}^2 + 2N\sigma_{xy}^2 - \bar{\sigma}^2 \tag{2}$$

MKi:

$$f(\sigma_{ij}-\alpha_{ij}) = (\sigma_{xx}-\alpha_{xx})^2 - (\sigma_{xx}-\alpha_{xx})(\sigma_{yy}-\alpha_{yy}) + (\sigma_{yy}-\alpha_{yy})^2 + 3(\sigma_{xy}-\alpha_{xy}) - \sigma_s^2 \tag{3}$$

where, $d\alpha_{ij} = c\dfrac{\sigma_{ij}-\alpha_{ij}}{\bar{\sigma}}d\bar{\varepsilon}^p$. And then α_{ij} can be obtained by integrations. x and y are the rolling direction and transverse rolling direction respectively. $\bar{\sigma}$ is the equivalent stress, $\bar{\varepsilon}^p$ is the equivalent plastic strain, σ_s is the yield stress, σ_{ij} and α_{ij} are the stress and back stress component respectively, F, G, H, and c are material constants which can be solved with material property data.

Nine pairs of rollers are designed according to the objective shape of the bumper with the commercial roller design software COPRA RF. The roller stand distance is 350 mm. Since the deformation of the specimen is symmetrical, half of the model is constructed to reduce the calculation time cost, and the assembly is shown in Fig. 3. At the beginning of the simulation, the bottom roller of the first pair of rollers is placed 20 mm below the sheet in order to build up the contact smoothly.

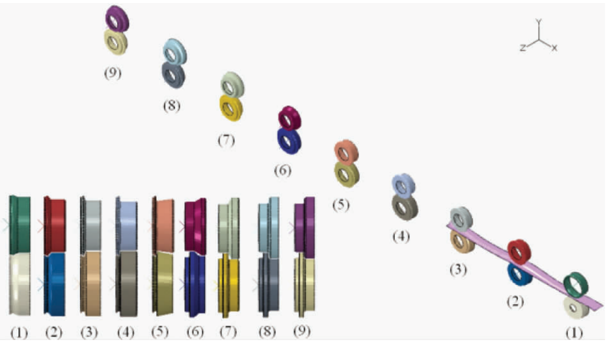
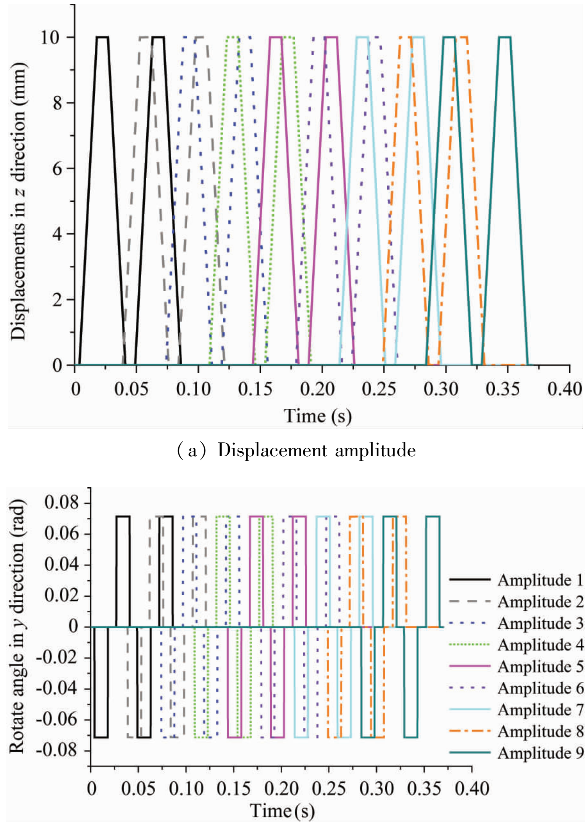


Fig. 3 Assembly of the flexible roll forming line in ABAQUS

As mentioned above, there are two approaches for modeling the roll forming process. If the first approach is adopted to model the flexible roll forming, rollers need to revolve around y direction as well as z direction. The settings of the rotations in two directions together with translations are very complicated, and it is difficult for ABAQUS to realize this kind of motion accurately because of its own calculation errors. While the second approach can well realize the simulation of the relative motions of the rollers, and the simulation results agree well with the experimental results in previous studies[8,9]. Therefore, the second approach is adopted in this study. The flexible roll forming simulation is realized in two steps. In the first step, the bottom roller of the first pair of rollers moves up and generates initial bending deformation. In the second step, the sheet is pulled through all the rollers by the leading edge. Each pair of rollers translates back and forth in z direction and revolves around y axis from time to time according to the designed path, which ensures that each roller plane keeps tangent with the main bending line. The translation and rotation of the rollers are realized by amplitude curves, which are shown in Fig. 4.

The explicit dynamic FEM method has proven valuable in solving quasi-static problems such as metal forming, the shortcoming of which is the confinement of the stability limit. The actual sheet speed is 28 mm/s, and the calculation time of this nine step roll forming process is 36 months with this speed because of the small size of the elements and the great number of the sheet elements. One method of improving the calculation efficiency is to increase the forming speed in simulations, but high speed may lead to dynamic effect and



(a) Displacement amplitude

(b) Rotation amplitude

Fig. 4 The displacements and rotation amplitude of rollers

may reduce the simulation accuracy. By repeatedly modifying the forming speed, 10 m/s is considered to be a reasonable speed in the simulation. With this speed, the calculated ratio of kinetic energy to internal energy is rather small, which indicates that the simulation is close to the real forming process, as shown in Fig. 5. And the simulation of the whole process carried out by the 8-CPU workstation takes three days, which is acceptable.

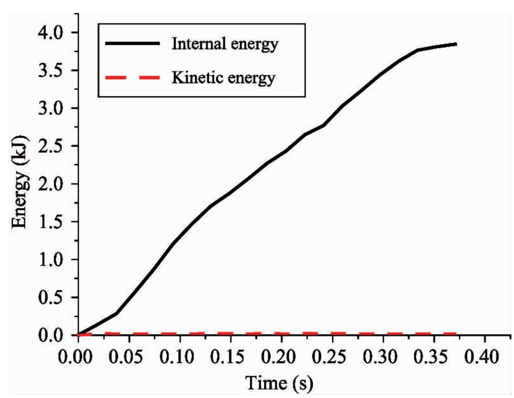


Fig. 5 Contrast of internal energy and kinetic energy

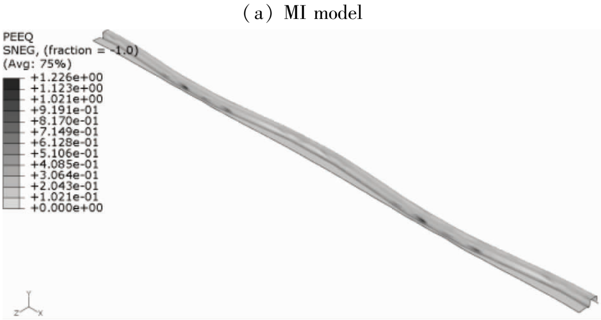
The penalty method and the Coulomb friction model are adopted. The penalty method approximates hard pressure-overclosure behavior. With this method, the contact force is proportional to the penetration distance, so some degree of penetration will occur. The basic concept of the Coulomb friction model is to relate the maximum allowable frictional (shear) stress across an interface to the contact pressure between the contacting bodies. The friction coefficient is assumed to be 0.1.

2 Simulation results based on different material models

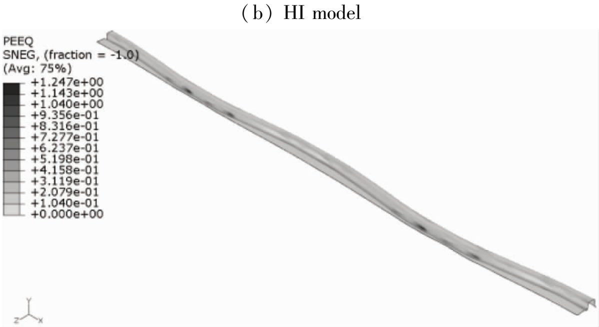
2.1 Strain distribution

The equivalent plastic strain distributions of the flexible roll formed part calculated with three material models are shown in Fig. 6. It is shown that in the longitudinal direction, the plastic strain of the varying positions of the cross sections is greater than other positions, while in the lateral direction, the plastic strain of the corners is greater than other positions. The maximum plastic strain of MKi model is the largest, and that of MI model is the smallest.

(a) MI model



(b) HI model



(c) MKi model

Fig. 6 Equivalent plastic strain of the final part calculated with three material models

2.2 Thickness of the cross section

The sheet experiences bending deformations under the bending force and friction force of the rollers. The material flow makes the sheet thickness change at different positions. Two typical cross sections are selected from the sheet, as shown in Fig. 7. The thicknesses of different cross sections of the sheet after springback is shown in Fig. 8. It can be seen that almost all the changes of the thickness are coincident with the corners of the bumper, and the sheet gets thinner obviously, while other part of the sheet remains approximately the original thickness: 1 mm. This indicates that the fracture defect is prone to appear at the corners of the parts. The general trend of the thickness distribution calculated with three material models are the same. The thickness reduction rates (thickness reduction divided by sheet original thickness) at the cross section a and b are shown in Table 1 and Table 2. It is shown that the thickness reduction rates of MKi model is larger than that of other two models, while the thickness reduction rates of MI model and HI model are close.

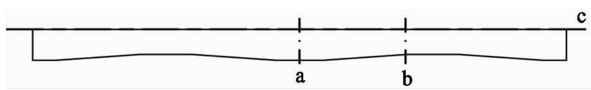


Fig. 7 Sketch of different cross sections on the blank sheet

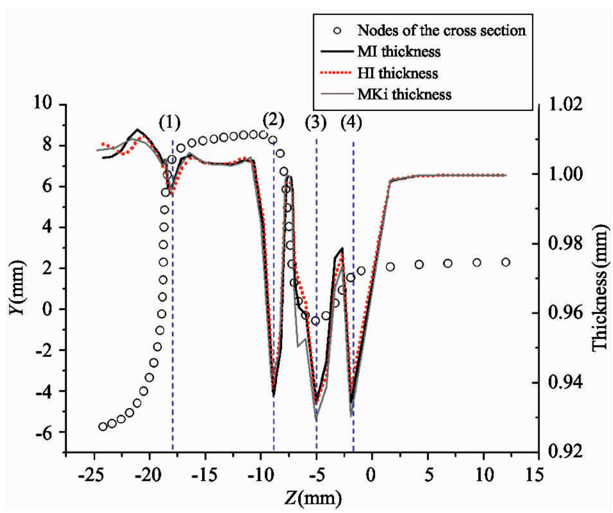


Fig. 8 Thicknesses calculated with three material models

Table 1 Thickness reduction rates at cross section a (%)

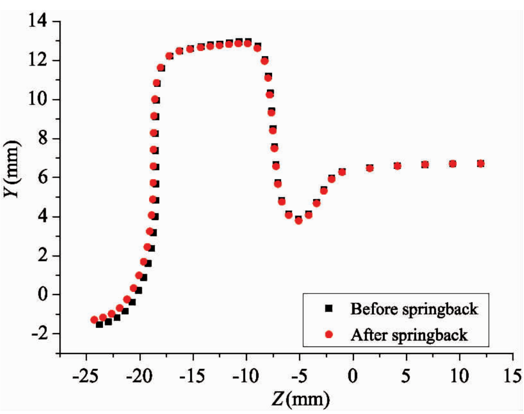
	(1)	(2)	(3)	(4)	Average
MI	0. 6	6.5	6.5	6.6	5.05
HI	0. 8	6.4	6.5	6.4	5.025
MKi	0. 7	6.0	7.2	7.0	5.225

Table 2 Thickness reduction rates at cross section b (%)

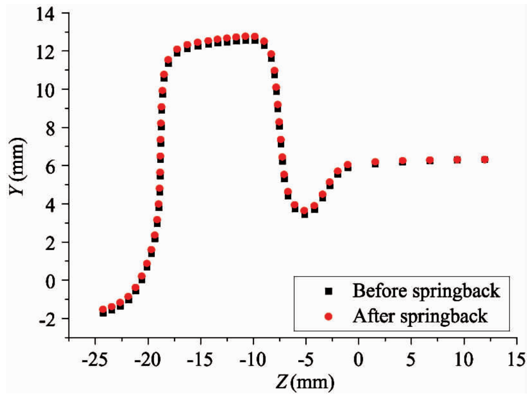
	(1)	(2)	(3)	(4)	Average
MI	0.4	6.8	5.6	5.8	4.65
HI	0.2	6.2	6.0	5.4	4.45
MKi	0.4	6.6	6.3	6.0	4.825

2.3 Springback amount

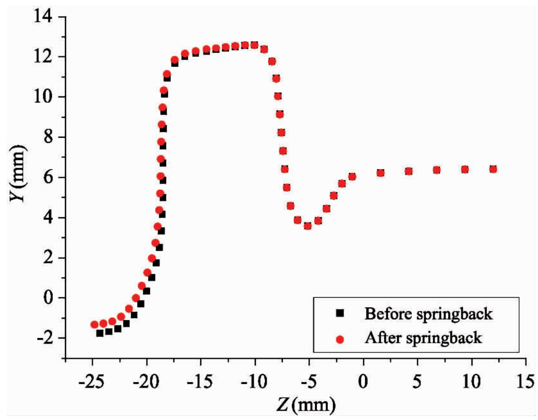
In the FEM simulation of the flexible roll forming, when the sheet leaves one pair of rollers and moves towards the next pair of rollers, it experiences springback. And when the rear of the sheet comes out of the last pair of rollers, the material has experienced springback to some extent, and the residual stress has been released partially. Therefore, in the simulation of the springback with the implicit algorithm, the lateral springback amount is very small. The springback mainly shows in the longitudinal direction. The springback amount calculated with different material models is shown in Fig. 9. From Fig. 9(a), (b), and (c), it can be seen that the springback amount in the lateral direction calculated with different material models are very small. Springback mainly occurred at the left end of the cross section. The left end springback amount in Y direction calculated with MI model, HI model, and the MKi model are 0.248mm, 0.186mm, and 0.434mm, respectively. And the springback amount of MKi model is much larger than the other two models. The longitudinal springback is shown in Fig. 9(d), (e), (f) and (g). In order to evaluate quantitatively, the longitudinal springback amounts at the left end and the right end calculated with different models are shown in Table 3. It is shown that the average longitudinal springback amount calculated with MKi model is larger than the other two models, and the springback amount difference calculated with MI model and HI model is only 0.01.



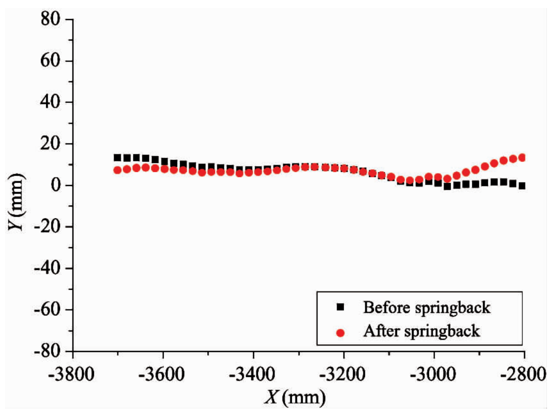
(a) MI model lateral springback



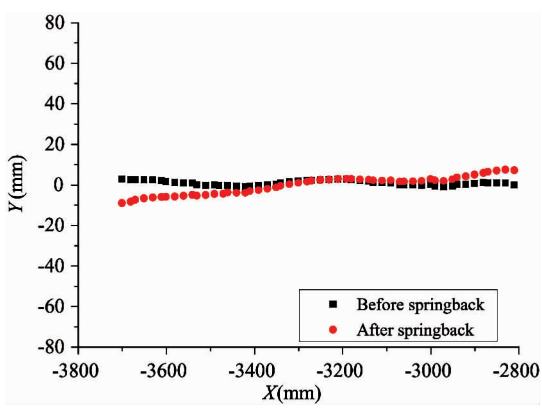
(b) HI model lateral springback



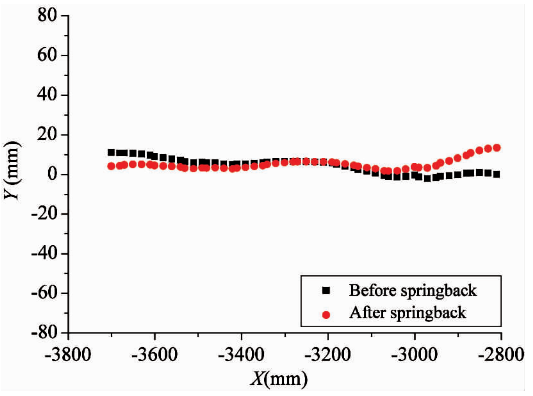
(c) MKi model lateral springback



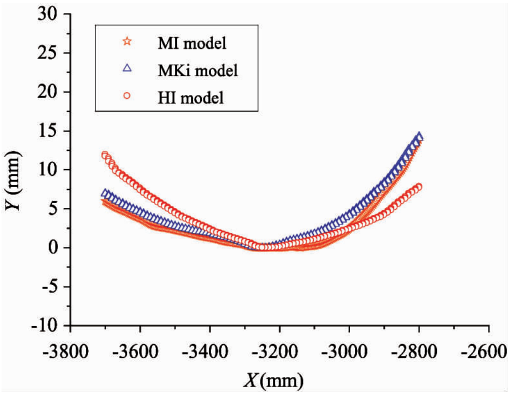
(d) MI model longitudinal springback



(e) HI model longitudinal springback



(f) MKi model longitudinal springback



(g) Longitudinal springback amount calculated with different models

Fig. 9 Springback amount in two directions calculated with three material models

Table 3 Longitudinal springback amounts in Y direction

	Left end(mm)	Right end(mm)	Average(mm)
MI model	5.98	13.83	9.91
HI model	11.97	7.86	9.92
MKi model	7.018	14.33	10.67

3 Conclusions

An FEM model of the nine-step flexible roll forming of an ultra-high-strength steel bumper is established. The forming step is simulated with the explicit algorithm, and the springback step is simulated with the implicit algorithm.

The sheet thickness analysis shows that the sheet thinning positions are at the bending corners. It is found that the sheet thicknesses calculated with MI model and HI model are very close, while the average thickness reduction rates calculated with MKI model are larger, which are 5.225% , 4.825% for the two typical cross sections.

With the analysis of the springback in both lateral and longitudinal directions, it is found that the springback amount predicted by MKi model is larger than the other two models. The average longitudinal springack of MI model, HI model and the MKi model at the two ends are 9.91 mm, 9.92 mm, 10.67 mm, respectively. The left end lateral springback amount in Y direction calculated with MI model, HI model, and the MKi model are 0.248 mm, 0.186 mm, and 0.434 mm, respectively.

With quantitative comparisons of thickness reduction and springback amount, it can be seen that the material models do have some influences on the flexible roll forming simulation results. Therefore, further experimental verifications need to be performed in order to find the best material model so as to obtain the most accurate simulation results.

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