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Stretch Bending of Z-section Stainless Steel Profile

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Abstract: The stretch bending properties of a new Z-section stainless steel profile were investigated by simulation. The causes of the forming defects, such as section distortions and poor contour precision, were analyzed, and the corresponding controlling methods were proposed. The results show that the main forming defects for the stretch bending of the Z-section profile were the flange sagging, the sidewall obliquing inward, the bottom surface upwarping, and the bad contour accuracy; the cross-section distortions were mainly induced by the shrinkage of the sidewall, which could be eliminated by increasing the sidewall height of the profile reasonably; the poor contour precision was mainly due to springback, which could be controlled by modifying the die surface based on the springback amount; for the investigated bending beam, the proper sidewall height compensation was 2 mm, and the suitable die surface modification amount was 1.2 times of the springback amount, when the elongation was 10% of the initial profile length. Stretch bending tests were conducted on a new type of die with adjustable bending surfaces, and high quality components were achieved, which verified the effectiveness of the defect controlling measures.

Key words: stretch bending; Z-section; profile; numerical simulation; rail vehicle

As one of the important approaches to solve the urban traffic problems, rail transportation such as subway and high-speed railway has received a lot of attention in recent years for its prominent advantages of large capacity, high efficiency, energy saving and environmental protection[1-4]. Rail vehicle body components with large size and complex section have strict requirements in section and contour accuracy, which creates a challenge for the manufacture of the high quality vehicle body. Stretch bending process is a high precision forming technology[5], and is one of the effective ways to overcome this challenge. During the process, the profile is bent and tangentially stretched at the same time, which can reduce the springback and improve the forming precision[6].

There are two main types of rail vehicle body materials, which are stainless steel and aluminum alloy[7-9]. At present, much research has been done on the bending of the aluminum alloy extrusions with various sections, while the research on the bending of the steel part with large geometry is relatively few. Liu et al.[10,11] investigated the influence of the rotary stretch bending process parameters on the cross-section distortion of the rectangular aluminum alloy tube. Nakajima et al.[12] developed a press bending technology for obtaining the extruded square tubes with highly accurate cross sections. Xiao et al.[13] studied the effects of the rotary stretch bending parameters on the forming quality of the double-ridged rectangular tube. Lăzărescu[14] investigated the effect of internal fluid pressure on the quality of aluminum alloy tube in rotary stretch bending. Clausen et al.[15] studied the influence of different stretch bending procedures on the forming quality of the aluminium extrusions with closed section for car bumpers. Deng et al.[16] researched the hot stretch bending and creep forming process of the titanium alloy profile with L-section. Liu et al.[17] investigated the springback behaviors of the Al-Li alloys extrusions with Z-section and T-section in stretch bending. Wang et al.[18] developed a multi-gripper flexible stretch forming device to improve the conforma-

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bility of sheet metal. Yu and Lin[19] studied the effect of processing parameters on the dimension precision of the U-shaped aluminium profile in rotary stretch bending. Yu and Li[20] developed the models for characterizing the springback angle after unloading based on the stress and strain distributions in the cross-section of the L-section extrusion part in rotary stretch bending. Li et al. [21] analyzed the bending process of the large diameter stainless steel pipe, combining with local heating or cooling by simulation.

With the updating of the design concept of the rail vehicle body, a new kind of stainless steel stretch-bent components with Z-section appeared. There are few literatures on the study of the stretch bending of the profile with this kind of section until now. To enhance the quality of the rail vehicle body, it is necessary to carry out a systematical study on the stretch bending of the Z-section stainless steel profile. Therefore, the stretch bending properties of a Z-section stainless steel bent beam on a rail vehicle was investigated by simulation, and the causes and corresponding controlling methods of the forming defects were analyzed. Besides, a new kind of bending die with adjustable forming surfaces was developed, and the stretch bending tests were conducted, which verified the correctness of this study.

1 Simulation Model for Stretch Bending

1.1 Stretch bending mechanism

Fig. 1 shows the stretch bending machine and the corresponding structure sketch. As shown, the bending die is fixed on the workbench; the profile is placed in the bending die, and the ends of the profile are clamped by the jigs. During stretch bending, the rotation of the jig drives the profile to bend around the die, and the motion of the jig makes the profile be stretched, which is beneficial for improving the stress distribution of the section and reduce the springback.

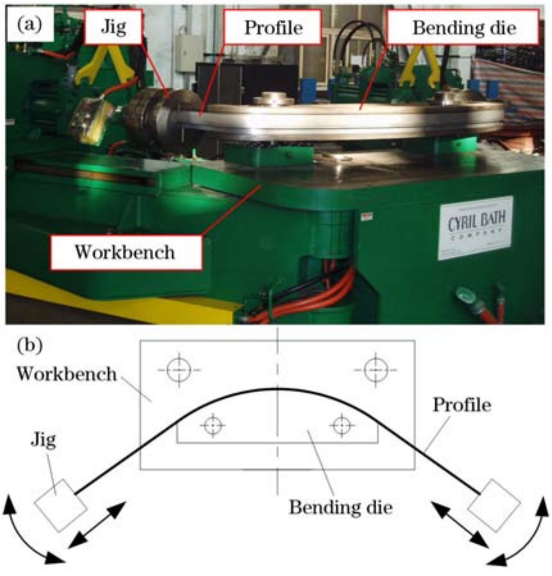


Fig. 1 Stretch bending machine (a) and structure sketch (b)

1.2 Simulation model

The investigated Z-section bent beam is shown in Fig. 2. The material is 2 mm SUS301L-ST stainless steel, and its mechanical properties are presented in Table 1. Based on the geometry of the component, the simulation model was established with the general finite element software ABAQUS, as shown in Fig. 3. Due to symmetry, half of the whole model was adopted. To enhance the calculation efficiency, the bending die, holder and jig were set as rigid shell, while the profile was set as deformable shell. The constitutive behavior of the profile was determined based on the Krupkowsky law and the Mises yield criterion was selected as the yield criterion. The contact behavior between the surfaces was expressed by the Coulomb model, assuming that the friction coefficient was 0.1. The profile was meshed by S4R element, and the global mesh size was 5 mm; while the tools were meshed by R3D4 element, and the global size was 10 mm. The fillet areas of the profile and the tools were locally refined with 0.5 mm meshes. The bending process was calculated with the dynamic explicit algorithm, and the springback process

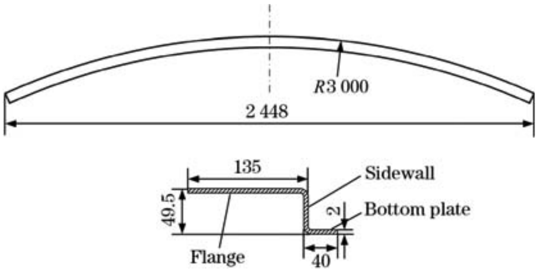


Fig. 2 Contour and cross-section characteristics of the Z-section bent beam (unit: mm)

Table 1 Mechanical properties of SUS301L-ST stainless steel

Parameter	Values
Density/($kg \cdot m^{-3}$)	7850
Elastic modulus/GPa	201
Poisson's ratio	0.33
Strength coefficient K/GPa	1.504
Hardening exponent n	0.3467
Yield strength/MPa	524.2

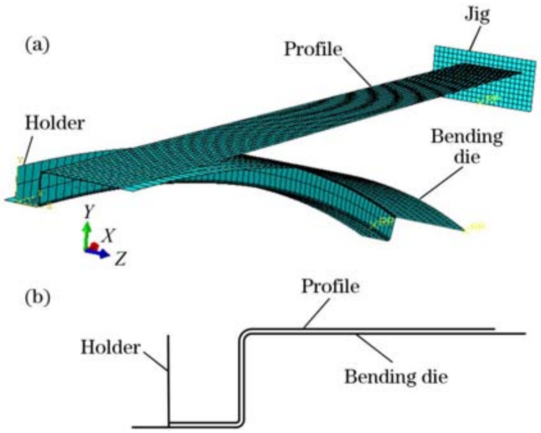


Fig. 3 Simulation model for stretch bending (a) and schematic diagram of middle section of the model (b)

was simulated with the static implicit algorithm.

In the simulation model for stretching bending, the bending die and the holder were fixed all the time; the middle section of the profile was applied with the symmetrical boundary condition, and the end of the profile was tied with the jig; the jig was applied with the motion boundary condition in the x and y directions and the rotation boundary condition in the z direction, respectively. Thus, the profile could be stretched and bent with the moving and the rotating of the jig.

To investigate the influence of the bending conditions on the forming quality of the Z-section beam, process parameters such as the total elongation and the structure parameters like the sidewall height of the profile were selected as the variables. Through the study on the influence law, the controlling methods of the forming defects can be found out, and the bent parts with high qualities can be manufactured.

1.3 Jig trajectory design

In stretch bending, the motion and the rotation of the jig are the motivation of the forming of the profile, so the moving trajectory of the jig is the key of the stretch bending simulation. Assuming that the profile completely contacts with the die surface during the bending process, the contact point between the profile and the die surface will also be the tangent point of the die surface curve. According to the geometric relations, the jig trajectory during the bending process can be calculated following the equations as:

$$\begin{cases} x_J = 2\ 999\sin\theta + (L + \Delta l - 2\ 999\theta)\cos\theta \\ y_J = 2\ 999(1-\cos\theta) + (L + \Delta l - 2\ 999\theta)\sin\theta \end{cases} \quad (1)$$

where, (x_J, y_J) is the jig coordinate; L is the initial profile length; Δl and θ are the elongation and the bending angle of the profile, respectively. When the elongation for the profile is 10% of the initial profile length and the die surface is the inner surface of the beam, the jig trajectory for the investigated beam is shown in Fig. 4, where the dotted line is the jig trajectory when the profile is only bent, while the solid line is the actual trajectory when the profile is stretched and bent simultaneously, and hence the distance between the two lines is the elongation of the profile.

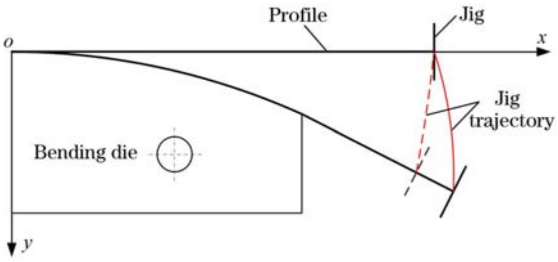


Fig. 4 Jig trajectory

2 Simulation Results and Discussion

2.1 Forming defects analysis

The stretch bending simulation results when the elongation was 10% of the initial profile length and the profile section was the same as the standard beam are shown in Fig. 5. It can be seen that serious section distortion arose after the profile was bent, such as the flange sagging, the sidewall obliquing inward, and the bottom plate upwarping. In addition, although the stretch bending process could reduce springback compared with other forming processes, the contour accuracy was poor due to the large springback, which originated from the large geometry of the beam.

The cause for the serious section distortion was the section shrinkage induced by the extension of the profile, in which the sidewall shrinkage had the most

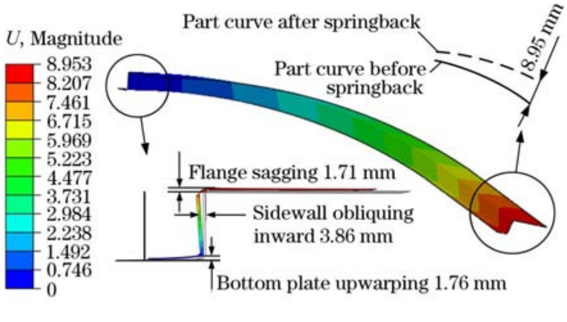


Fig. 5 Stretch bending defects when elongation was 10% of initial profile length and profile section was same as standard beam

influence on the deformation of the section. Fig. 6 shows the material flow trends of the profile during stretch bending. It can be seen that in the longitudinal direction, the material flowed to the end and the profile was extended; in the horizontal direction of the section, the inward flowing of the material in the flange and the sidewall made the sidewall oblique, which reduced the rigidity of the sidewall and then led to the sagging of the flange in the fillet position; in the vertical direction of the section, the upward flowing of the material in the bottom plate made the upwarping of the bottom plate.

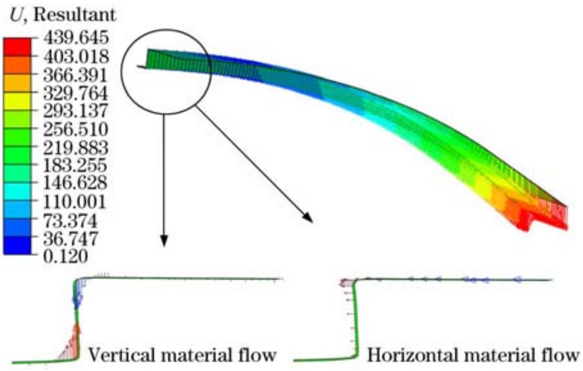


Fig. 6 Material flow trends of profile during stretch bending

2.2 Section distortion control

As known from the above analysis, the main reason for the section distortion is the sidewall shrinkage. There are two main ways to control the deformation of the section, which are adjusting the process parameters and increasing the sidewall height to compensate the shrinkage of the sidewall. The flange sagging amount was selected to evaluate the effects of the two methods to control the section distortion.

The influence of the elongation on the section distortion is shown in Fig. 7, in which the negative value represents the flange sagging. It can be seen that more serious section distortion appeared as the elongation increased, while the declining of the sagging amount was not obvious with decreasing the elongation.

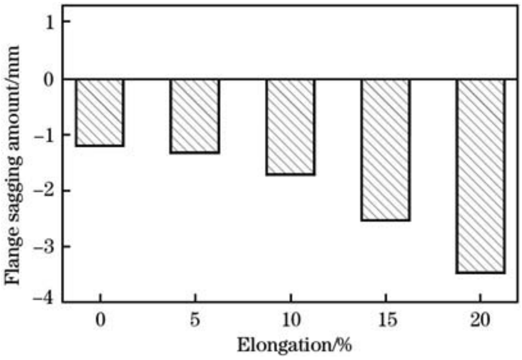


Fig. 7 Flange sagging degrees for different elongations when profile section was same as standard beam

The sagging degrees of the flange for different sidewall heights are shown in Fig. 8, in which the positive value means the flange upwarping, and H means the sidewall height of the standard beam. The corresponding section deformations are presented in Fig. 9. It can be seen that when the sidewall height was smaller than H, the flange sagging was more serious (Fig. 9(a)); as the sidewall height increased, the flange sagging degree obviously decreased, and the section distortion was effectively controlled (Fig. 9(b)); however, when the sidewall height was over compensated, new section distortion of flange upwarping appeared (Fig. 9(c)).

Therefore, the effective way to control the sec-

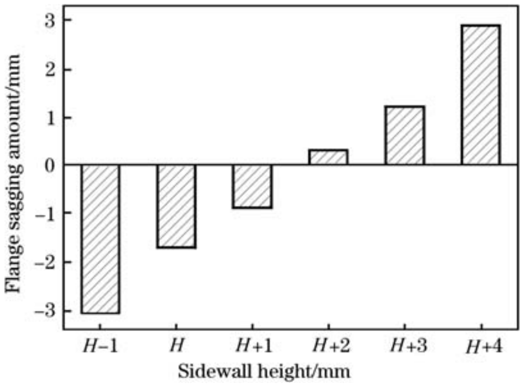
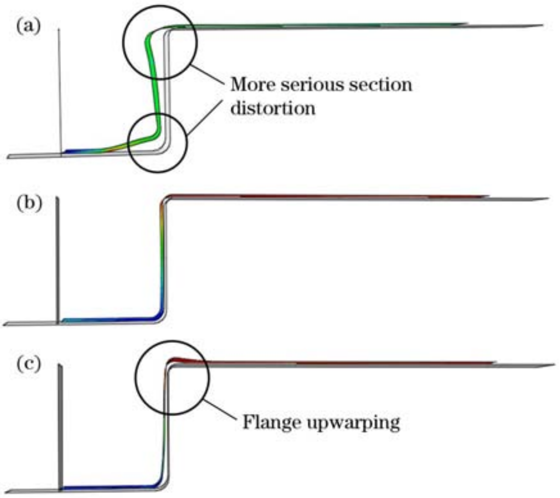


Fig. 8 Flange sagging degrees for different sidewall heights when elongation was 10% of initial profile length



(a) $H-1$; (b) $H+2$; (c) $H+4$.

Fig. 9 Section deformation of the bent parts for different sidewall heights when elongation was 10% of initial profile length tion distortion of the Z-section profile in stretch bending is to increase the sidewall height reasonably. For the investigated bent part in this work, the proper sidewall height compensation is 2 mm when the elongation is 10% of the initial profile length.

2.3 Contour accuracy control

The ways to control the contour accuracy are mainly by adjusting the process parameters or modifying the bending surface of the die. The contour accuracy deviations for different elongations and die surface modification amounts are shown in Figs. 10 and 11, respectively. It can be seen that although increasing the elongation could improve the contour accuracy to some extent, the deviations were still over the general accuracy requirement for the rail vehicle body components, which was 1 mm; the contour accuracy could be effectively controlled by proper die surface modification based on the springback amount. For the investigated beam in this work, the proper die surface modification is 1.2 times of the springback amount when the elongation is 10% of the initial profile length.

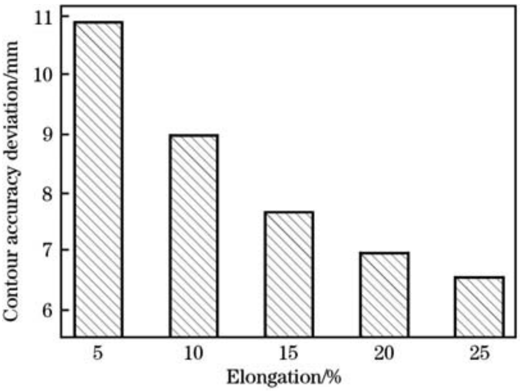


Fig. 10 Contour accuracy of bent parts for different elongations

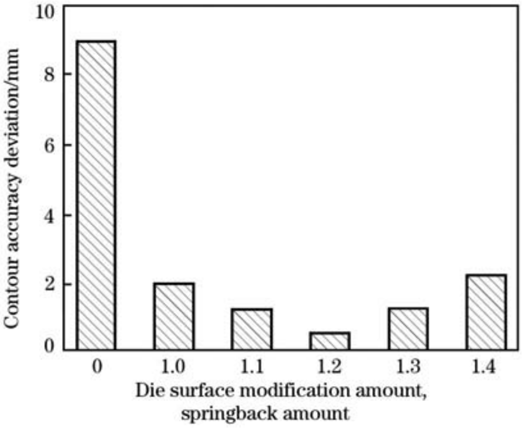


Fig. 11 Contour accuracy of bent parts for different die surface modification amounts when elongation was 10% of initial profile length

3 Stretch Bending Tests

It can be known from the simulation results that when the elongation is 10% of the initial profile length, to gain the qualified component, the sidewall height should be 2 mm higher than that of the standard beam, and the die surface should be modified with 1.2 times of the springback amount. In order to verify the correctness of the conclusion, a new kind of stretch bending die with adjustable forming surface was developed, as shown in Fig. 12. This bending surface of the die was made up of many small base bulks, and each surface of the bulk was designed as cylindrical to avoid scratching the profile. The bending surface could be modified by adjusting the relative heights of the base bulks, which canceled the reprocessing of the die, and was advantageous to achieve the high precise components. Stretch bending tests were conducted by setting the proper process parameters, as well as the reasonable profile section and die surface, as shown in Fig. 13. The test results in Fig. 14 showed that high quality bent parts with high contour accuracy and little section distortion were produced.

Fig. 12 Stretch bending die with adjustable forming surfaces

Fig. 13 Stretch bending test

Fig. 14 Test part with high contour accuracy (a) and little cross section distortion (b)

4 Conclusions

(1) The main forming defects for the stretch bending of the Z-section profile are the section distortions and the poor contour accuracy. The section distortions include the flange sagging, the sidewall obliquing inward and the bottom surface upwarping.

(2) The section distortions of the Z-section stretch bent part are mainly induced by the sidewall shrinkage. The section distortions can be effectively eliminated by increasing the sidewall height reasonably to compensate the shrinkage of the sidewall during stretch bending.

(3) The poor contour accuracy of the Z-section stretch bent part mainly originates from springback. Compared with increasing the elongation, modifying the die surface based on springback can better improve the contour accuracy.

(4) For the investigated Z-section beam, the proper sidewall height is 2 mm higher than that of the standard beam, and the suitable die surface modification is 1.2 times of the springback amount when the elongation is 10% of the initial profile length.

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