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Research Article

Effect of Mandrel on Cross-Section Quality in Numerical Control Bending Process of Stainless Steel 2169 Small Diameter Tube

Jun Fang,[1,2] Shiqiang Lu,[2] Kelu Wang,[2] Jianmei Xu,[2] Xiaomei Xu,[2] and Zhengjun Yao[1]

[1] *Institute of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*
[2] *School of Materials Science and Engineering, Nanchang Hangkong University, Nanchang 330063, China*

Correspondence should be addressed to Shiqiang Lu; niatlusq@126.com

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The tube numerical control (NC) bending process is a much complex physical process with multifactors coupling interactive effects. The mandrel is the key to improve forming quality and to enhance forming limit. In this study, based on the platform of ABAQUS/Explicit, a 3D elastic-plastic finite element model of NC bending process of 2169 (0Cr21Ni6Mn9N) stainless steel tube was established, key technological problems were solved, and its reliability was validated. Then, simulation and analysis of the processes were carried out, and the influence laws of mandrel types and mandrel parameters on cross-section quality were obtained. The results show that the wall thinning or cross section deformation is serious at the middle part and small in the vicinity of the bending plane or initial bending plane; the wall thinning degree increases or the cross section deformation degree decreases with the increase of mandrel diameter or mandrel extension length; the effect of bulb mandrel on the cross section quality is more significant than that of cylinder mandrel. And the reasonable mandrel types and mandrel parameters are chosen for the 2169 high-pressure hydraulic tube with small diameter. The results may lead to better understanding of mandrel role in the improvement of forming quality and forming limit in the NC bending process.

1. Introduction

Tube bending parts have many desirable features, such as reducing the weight, strengthening the structure, and absorbing the impact energy and shock. As a result, they have been attracting more and more applications in aviation, aerospace, automobile, and ship [1]. The rapid development has posed an urgent requirement for the exploitation of advanced plastic-forming technology to bend high-quality tube parts. Among the various bending processes, the NC bending process, based on a rotary draw bending method, has become one of the advanced technologies satisfying the above requirements, due to its many unique advantages, such as high efficiency, economy, process stability, and easier to enable digital precision forming process and mass production [2].

However, in the NC bending process of stainless steel 2169 tube with small diameter, the tube is subjected to tension stress on extrados, compression stress on intrados, and compression stress in the radial direction, respectively, so that there is thinning or even cracking on extrados and thickening or even wrinkling on intrados. Meanwhile, the centripetal resultant forces make the tube cross section to be distorted. Cracking and wrinkling can be avoided, but the wall thinning and the cross section deformation are inevitable. Thus, both the cracking and wrinkling should be avoided firstly; then, the wall thinning and the cross section deformation should be controlled to some acceptable extent in the NC bending process.

In order to reduce the wrinkling risk and cross section deformation degree, it is considered to fill the tube with fine sand, fluid, or rosin-cerate [3]. But it is known that filling the mediums such as sands or fluid may decrease the forming precision in production process and add pretreatment and posttreatment processes such as sealing, removing sealing, and cleaning, thus, increasing forming cost and environmental pollution, and so on, which seems difficult to satisfy the requirements of advanced NC bending process. While the mandrel can conquer the above problems due to its advantages of design ability, much flexibility, and relatively little cost. The mandrel plays an important role in improving both the forming quality and forming limit. So the research on the effect of mandrel on cross section quality is of great significance in the tube NC bending process.

Many scholars have carried out the researches on the wall thickness change and cross section deformation of tubes during bending process using theoretical analysis, experimental research, and the finite element method (FEM) simulation. By using plastic-deformation theory, Tang [4] derived the formulas for wall thickness change and cross section deformation. Strano [5] presented the expression for the maximal cross section deformation degree based on the experimental date of steel tube bending. Veerappan and Shanmugam [6] gave a mathematical relationship among the pressure ratio, ovality, thinning, tube ratio, and bend ratio. Wang and Agarwal [7] predicted the cross section deformation and wall thickness change of tubes in bending process under axial force and internal pressure. Pan and Stelson [8] used energy principle to solve the cross section deformation and wall thickness change of plastic tube bending. But, using the above formulas, it is difficult to find the characteristics in wall thickness change and cross section deformation of tube NC bending process.

By FE and experimental analysis, Zhan et al. [9] studied the various in wall thickness and cross-section under various operating parameters and mandrel parameters for the NC bending of TA18 tubes and presented a method for quickly determining the range of the axial mandrel feed. Li et al. [10–14] researched the deformation behavior of wall thickness and cross-section of NC bending of stainless steel and aluminum alloy tubes under different bending conditions, including the bending for the tube with large diameter and/or small bending radius [10, 11], the push assistant loading conditions [12], the role of mandrel [13], and different clearance between tube and dies [14]. Yang et al. [15] addressed the effect of frictions on cross section quality of thin-walled tube NC bending and obtained the reasonable friction conditions in the process. Jiang et al. [16] revealed the laws of cross section deformation and wall thickness change during NC bending of TA18 tubes with different bending radii. Yang et al. [17–19] experimentally investigated the influence of process parameters and geometric parameters on forming quality of thin-walled NC bending tube. Though the above researches mainly focus on the effect of process parameters and geometric parameters on forming quality of thin-walled tube NC bending, and study on the effect of mandrel on cross section quality is still scant [9, 13, 17], they could provide a reference for relevant investigation of stainless steel 2169 small diameter tube NC bending.

Therefore, in the study, a 3D elastic-plastic FE model of the NC bending process is established using the dynamic explicit FE code ABAQUS/Explicit (ABAQUS, 2011); then, the effect of mandrel on cross section quality of the tube NC bending has been studied. The achievements of this study are useful to select reasonable mandrel types and parameters in the process, and the method of numerical simulation can be used to study the influences of other parameters on the forming quality and forming limit of tube NC bending process.

2. Forming Principle of Tube NC Bending and Its Cross Section Quality

Figure 1 shows the sketch of the NC bending process and stress strain state. As shown in Figure 1(a), bending die is fixed on the major axes of machine tool and revolves together with the major axes. The pressure die is set on outer part, the wiper dies set on inner part of tube bending, and the mandrels set in the tube at the tangent point between the tube and bending die. Pulled by bending die and clamp die, the tube goes past the tangent point and rotates along the groove of bending die to desired bending angle and bending radius; then, the mandrel retracts, and the tube is unloaded.

Figure 1(b) shows the stress strain state of bent tube during NC bending process. Node A in the extrados is under tension stress in both tangent and hoop directions and compressive stress in radial direction; meanwhile, node B in the intrados is under 3D compressive stress state. This will lead to thinning or even cracking on extrados and thickening or even wrinkling on intrados. Meanwhile, both the composite force of tangent stress of outer part and that of inner part point to the center of the cross section of the tube, which causes the cross section deformation as shown in Figure 2(a).

The essential dies and the cooperation between them are needed to accomplish the tube bending process to ensure the free-wrinkling and allowed wall thinning and cross section deformation degrees. The pressure die is to apply enough pressure force and bending moment to the tube and push it against the wiper die tightly ensuring the free-wrinkling bending tube. At same time, the moving pressure die helps pushing the materials into bending regions reducing the wall thinning degree. The wiper die and mandrel are used to prevent the tube from wrinkling and over cross section deforming; especially the mandrel extension length plays an important role in that. The mandrel extension length e refers to the mandrel body extension length exceeding the bending tangent point (the point where the tube will begin to bend) as shown in Figure 1(a). The wiper die neck in the bending die grooves with its very thin tip extending to the bending tangent point. In doing so, it fills up the gap normally left by the bending die. Thus, the tube is completely confined and does not have space to wrinkle.

A few indices are used to measure the wall thinning degree and cross section deformation degree of NC bending of 2169 stainless steel tubes; the ratio of wall thinning (Δt) is expressed as

$$\Delta t = \frac{t - t'}{t} \times 100\%, \tag{1}$$

where t is the initial wall thickness of the tube; t' is the wall thickness at the thinnest point along the tube extrados after bending deformation as shown in Figure 2(b).

Due to the boundary constraints shown in Figure 2(b), the tube is constrained in transverse direction by bending die groove and under free deformation conditions in vertical direction. Thus, in NC bending process, the cross section

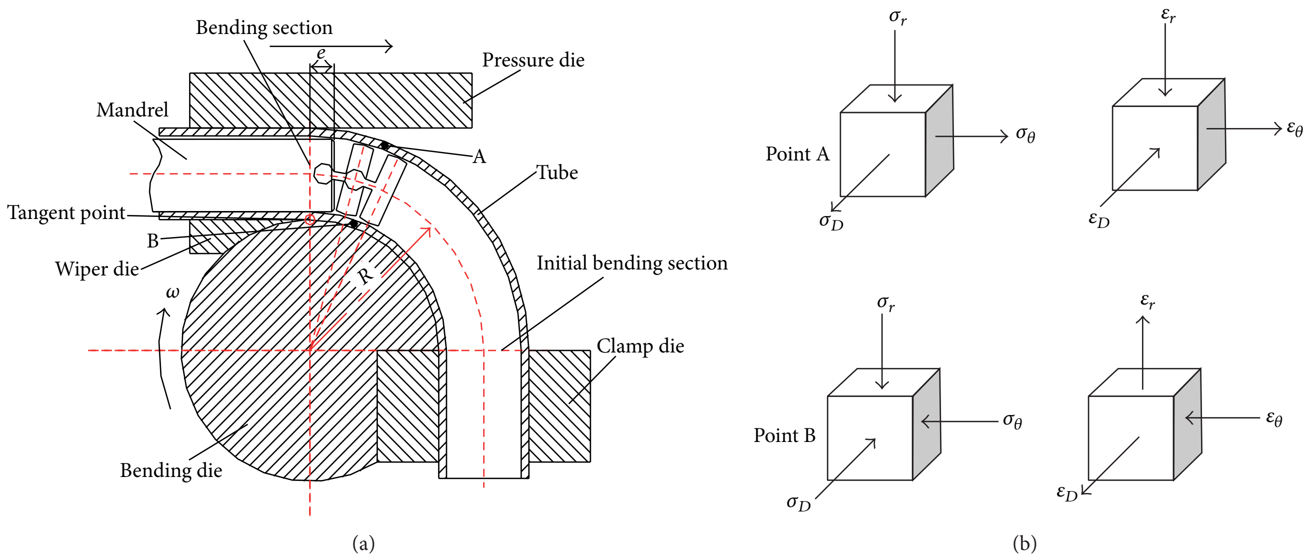


FIGURE 1: Sketch of the NC bending process (a) and stress stain state (b).

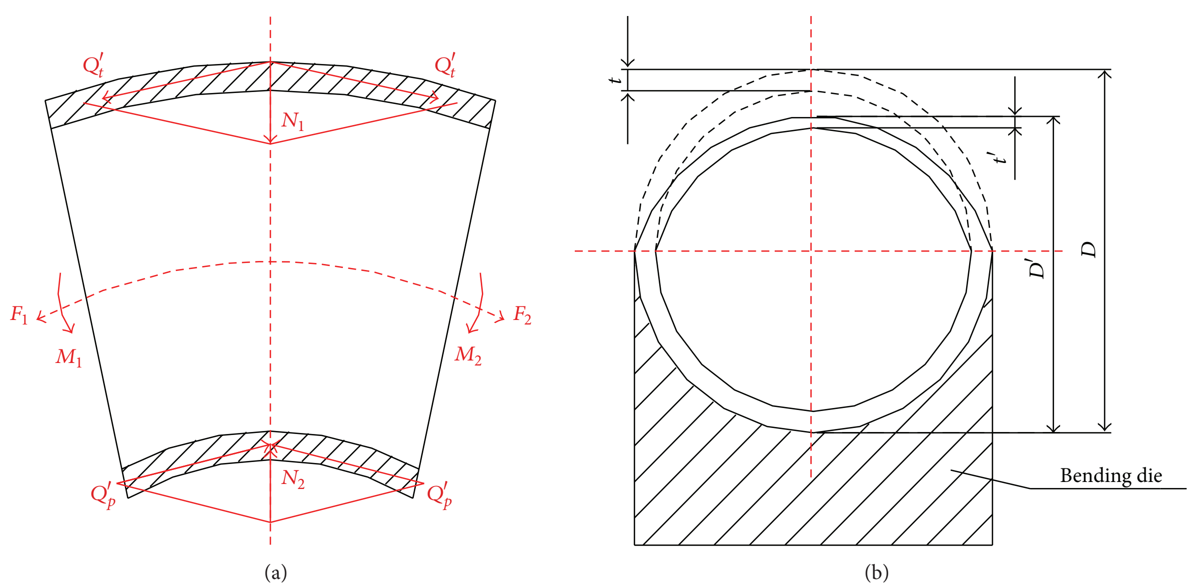


FIGURE 2: Cross section deformation and wall thinning of tube NC bending.

deformation (ΔD) can be determined by the changing ratio of the vertical magnitude of the cross section as

$$\Delta D = \frac{D - D'}{D} \times 100\%, \tag{2}$$

where D is tube initial outer diameter; D' is the cross section length in the vertical direction after bending as shown in Figure 2(b).

3. FEM Modeling and Key Technologies Resolved

Compared with the static implicit algorithm, the dynamic explicit finite element algorithm is the main method for simulating the 3D metal plastic forming process because of the unique advantages such as lower solution cost, few difficulties in simulating the complex contact and large deformation in metal forming process, and also ability of predicting wall thinning and cross section deformation phenomena directly, without iteration and convergence tolerance. So,

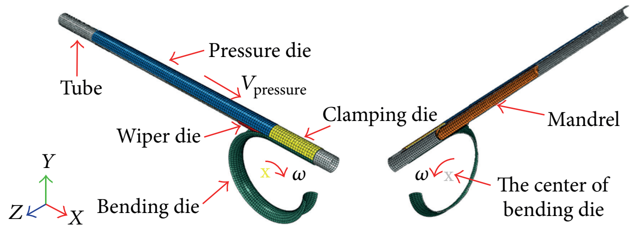


FIGURE 3: Finite element model for NC bending process of 2169 small diameter tube.

the elastic-plastic dynamic explicit finite element algorithm is chosen for simulating the NC tube bending.

Based on the above analysis and the platform of ABAQUS/Explicit (ABAQUS, 2011), a 3D elastic-plastic finite element model of the NC tube bending process is established (shown in Figure 3). To simulate the quasi-static metal forming process using the explicit algorithm exactly, the key technologies such as element type, friction condition, materials properties, and contact condition are resolved reasonably.

3.1. Geometry Modeling and Element Type Selection. Figure 3 shows a representative finite element model for NC bending of small diameter tube. In this model, tube is a deformable body. Forming dies, including bending die, clamp die, wiper die, pressure die, and mandrel, are simplified as rigid bodies for improving computational precision and efficiency.

The four-node doubly cured thin shell S4R is adapted to describe the tube with the following features: reduced integration and hourglass control. Five integration points are selected across the thickness to describe the tube bending deformation better. The rigid body surfaces of dies are described by four-node 3D bilinear quadrilateral rigid element R3D4 to simulate smooth contact geometry curved face. The mesh size of tube is 0.8×0.8 mm and that of rigid body surfaces is 1×1 mm.

3.2. Material Model. Correct material model determines the credibility of the finite element simulation. The material used in the simulations is an isotropic, homogeneous, elastic-plastic material following the von Mises yield criterion, with isotropic work hardening. The uniaxial tension test is used to obtain the mechanical properties of 2169 stainless steel tube (shown in Table 1) according to the GB/T228-2002 [20] using a WDW-100 electronic universal testing machine. And the Ludwigson model is used to describe the stain-hardening of austenitic stainless steel tube material as follows:

$$\overline{\sigma} = K\overline{\varepsilon}^{n} + e^{(a-b\overline{\varepsilon})}, \tag{3}$$

where a, b are constants.

3.3. Friction Model. In the tube NC bending process, the friction has an important influence on the deformation, so it is necessary to select a proper friction model into the finite element simulation. As there is a relative sliding phenomenon between the different contact interfaces, including tube-bending die, tube-clamp die, tube-wiper die, tube-pressure die, and tube-mandrel. So the Coulomb friction model is chosen to represent the friction behaviors between tube and dies. And the different friction coefficients have been assigned to the different contact interfaces as shown in Table 2. The friction coefficient between tube and clamp die is assigned a large value to satisfy the no slipping in the clamp interface. In ABAQUS, so-called "rough" friction with coefficient ∞ is available, where it is assumed that there is no bound on the shear stress, and thus, no relative motion can occur as long as the surfaces are in contact.

TABLE 1: Material properties of 2169 stainless steel tube.

Material parameters	Value
Young's modulus E (GPa)	197
Poisson's ratio ν	0.29
Initial yield stress $\sigma_{0.2}$ (MPa)	987
Hardening exponent n	0.177
Strength coefficient K (MPa)	1796.5
Ultimate tension strength σ_b (MPa)	1112
Extensibility δ (%)	22
Density ρ (kg/m^3)	7830
Constant a	5.7
Constant b	27.4

TABLE 2: Friction coefficients in various contact interfaces.

	Contact interface	Friction coefficients
1	Tube-bending die	0.1
2	Tube-pressure die	0.25
3	Tube-clamp die	Rough
4	Tube-wiper die	0.1
5	Tube-mandrel	0.05

3.4. Dynamic Boundary Constraints and Loadings. For contact pairs, the "surface-to-surface contact" method is used to define the contact between tube and dies. "Kinematic constraints" method is used to describe mechanical constraints for contact pairs except for the tube-mandrel interface which is simulated with "penalty method." Moreover, according to the real conditions, the sliding formulation for every contact interfaces is the "Finite sliding" except the one for tube-clamp die contact pair with the "Small sliding," namely, not being allowed for sliding between the tube and the clamp die.

The boundary constraints and loadings are applied by two approaches: "Displacement/rotation" and "Velocity/angular velocity." For the NC bending process with the bending radius 19.05 mm and the bending angle 180 degree, the bending time needed is 7.85 s at the bending angular velocity of 0.4 rad/s.

Both bending die and clamp die are constrained to rotate along the global Z-axis, while the pressure die is constrained to translate only along the global X-axis with the same linear speed as the centerline bending speed of the bending die. The wiper die is constrained along all degrees of freedom. The mandrel is fixed from all degrees of freedom

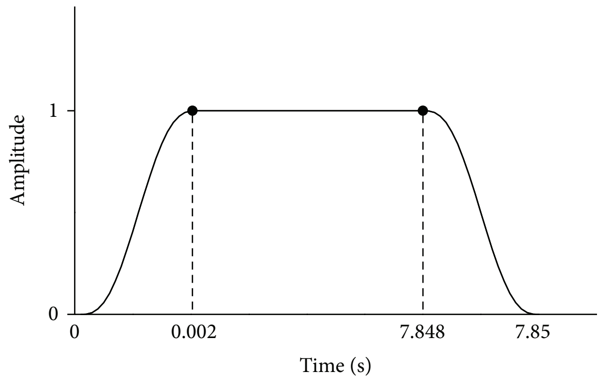


Figure 4: Smooth step amplitude curves.

in the tube bending process. After the bending process is finished, the mandrel will be withdrawn along the global X-axis. The smooth step amplitude curves are defined describing the change of the velocity with time as smooth as possible to ensure little inertial effects in explicit finite element simulation of quasi-static process as shown in Figure 4.

3.5. Finite Element Model Validation. In order to validate the 3D elastic-plastic finite element model of NC bending process, simulations for TA18 titanium alloy tube with the size of 14×1.35 mm (denoted $D \times t$, where D and t are the tube diameter and tube wall thickness, respectively) have been carried out based on the experimental conditions in [21]. The comparison of simulation result with the experimental result gotten in [21] is shown in Figure 5. From Figure 5, it is discovered that the result of simulation and that of experimental agree with each other. The maximum relative error of wall thinning degree between the simulation and the experimental result is less than 2% as shown in Figure 5(a), and the maximum relative error of cross section deformation degree between the simulation and the experimental result is less than 8% as shown in Figure 5(b). So it indicates that the 3D elastic-plastic finite element model built above is credible.

4. Results and Discussion

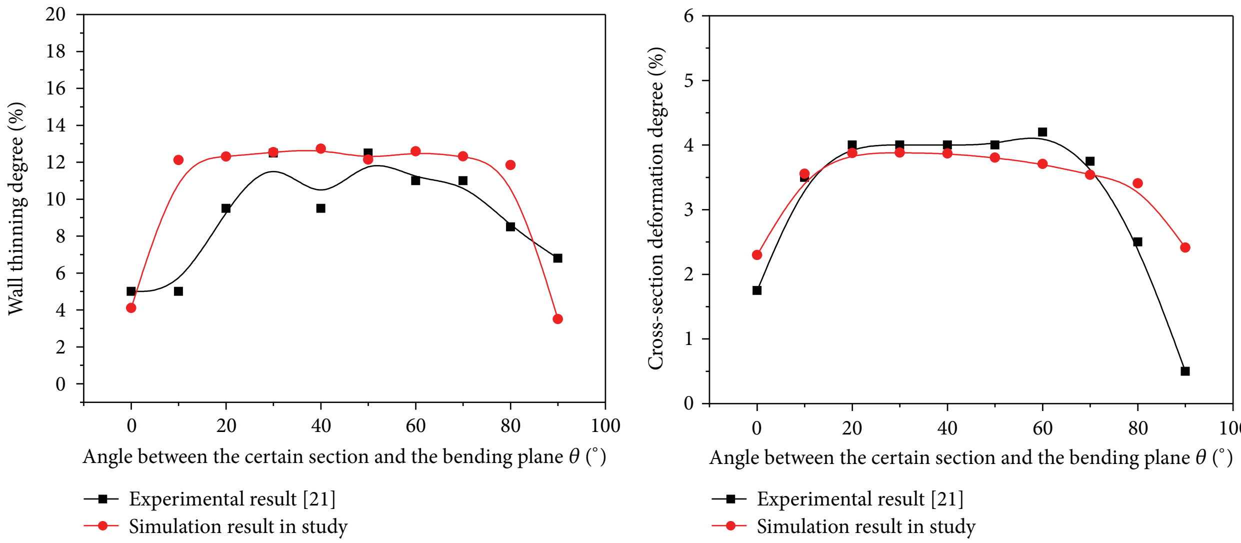
Using the established 3D elastic-plastic finite element model, the effect of the mandrel on cross section quality has been revealed. Using the hard mandrel (cylinder mandrel and bulb mandrel are shown in Figure 6) or without mandrel during small diameter tube bending process in general. Thus, the effect of mandrel types on cross section quality is modeled, and the appropriate mandrel is chosen based on the simulation results firstly. Then, the effects of the diameter and the extension length of mandrel on cross section quality are modeled based on the appropriate mandrel. The diameters of mandrel are 5.43 mm, 5.33 mm, and 5.23 mm, respectively, the mandrel extension lengths are selected as 0 mm, 1 mm, and 2 mm, respectively, and the fillet radius of the cylinder mandrel is 0.5 mm. Other parameters are shown in Tables 1, 2, and 3. Cracking and wrinkling are not found in the simulation, which provides the basis for the further research on the wall thinning and cross section deformation.

4.1. Effect of Mandrel Types on Cross Section Quality. The bending processes without mandrel or with cylinder mandrel and bulb mandrel have been simulated, respectively. The mandrel diameter is 5.43 mm, and the mandrel extension length is 2 mm.

Figure 7(a) shows the wall thinning degree without mandrel or with various mandrels. It can be seen that the wall thinning is serious at the middle part and small in the vicinity of the bending plane or initial bending plane. The wall thinning degree firstly increases then hardly changes and finally decreases along the bending direction from the bending plane to the initial bending plane. The maximum wall thinning degree without mandrel is 6.94%, while the maximum wall thinning degree with cylinder mandrel or bulb mandrel is 12.1%, 13.6%, respectively. It is because that mandrel-tube contact will produce friction force, which baffles the flowing of material and accordingly causes larger tangent strain and more serious tube wall thinning. The more the contact surface between mandrel and tube is, the larger friction force is. Thus, the maximum wall thinning degree with bulb mandrel is the largest.

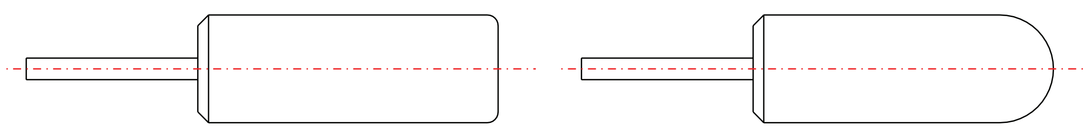
The cross section deformation degree without mandrel or with different mandrels is shown in Figure 7(b). It is found that the cross section deformation is serious in the midst of the bending deformation area and small near the initial bending plane and bending plane. This is because sections near the bending plane are supported by mandrel and restrained by mold cavity and sections in the vicinity of the initial bending plane are restrained by mold cavity, while sections in the midst of the bending deformation zone lie in the suspended state. When the mandrel is not used, the section, located at the angle of 50° with the bending plane, distorts most seriously and its cross section deformation degree is about 10.9%, which exceeds the requirement of the aerial standard. When the cylinder mandrel or bulb mandrel is used, the section, located at the angle of 30° with the bending plane, distorts most seriously and its cross section deformation degree is about 3%, 1.8%, respectively, which satisfies the requirement of the aerial standard. From the above results, it can be found that mandrel improves the cross section deformation significantly. This is because of the support of mandrel, and the bulb mandrel can support a wider range of curved surface of the bent tube. Therefore, taking both thinning and cross section deformation into consideration, the bulb mandrel was chosen properly in this paper.

4.2. Effect of Mandrel Diameter on Cross Section Quality. The mandrel diameter is a significant dimension parameter since it greatly influences the cross section quality of the bent tube. In this paper, the finite element simulation of the bending processes with the mandrel diameters of different sizes 5.23 mm, 5.33 mm, and 5.43 mm have been carried out, respectively. The bulb mandrel is used, and the mandrel extension length is 2 mm.



(a) (b)

Figure 5: Comparison of simulation result with experimental result [21]: (a) wall thinning; (b) cross section deformation.

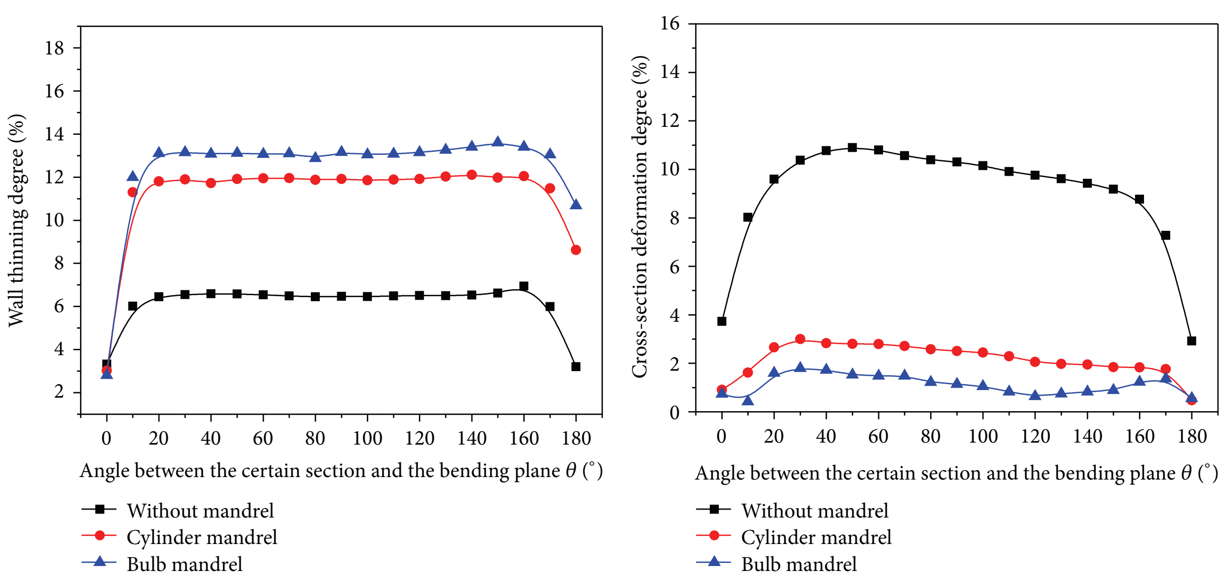


(a) (b)

Figure 6: Types of the hard mandrel: (a) cylinder mandrel; (b) bulb mandrel.

Table 3: Simulation parameter.

Tube diameter D (mm)	Tube wall thickness t (mm)	Bending radius R (mm)	Bending angle θ (deg)	Bending angular velocity ω (rad/s)	Clearance between tube and dies ΔC (mm)
6.35	0.41	19.05	180	0.4	0.1



(a) (b)

Figure 7: Effect of mandrel type on cross section quality: (a) wall thinning; (b) cross section deformation.

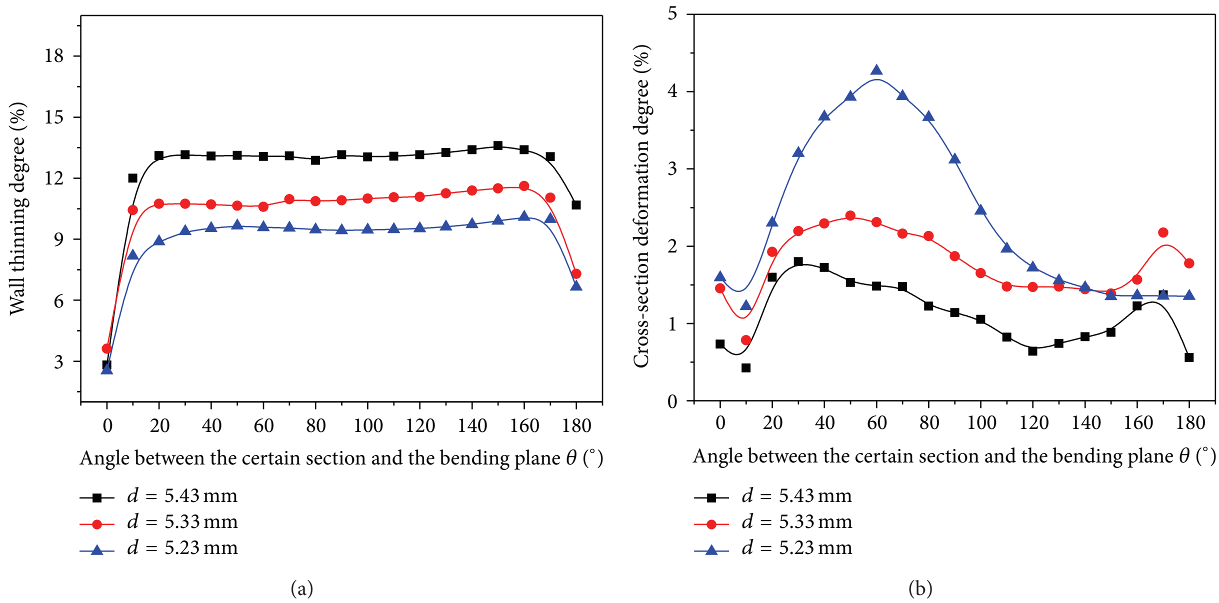


Figure 8: Effect of mandrel diameter on cross section quality: (a) wall thinning; (b) cross section deformation.

The wall thinning degree with different mandrel diameters is shown in Figure 8(a). It is found that the larger the mandrel diameter is, the larger the wall thinning degree of bent tube is. These results are similar to those of the NC bending for TA18 tube [9], but the effects of the mandrel diameter on wall thinning are more obvious in this work. The maximum wall thinning degree with mandrel diameter of 5.23 mm, 5.33 mm, and 5.43 mm is 10.1%, 11.6%, and 13.6%, respectively. This is because the large mandrel diameter increases the friction between the mandrel and the inside wall of tube and accordingly causes larger tangent strain and more serious wall thinning of bent tube.

Figure 8(b) shows the cross section deformation degree with various mandrel diameters. It can be seen from Figure 8(b) that the larger the mandrel diameter is, the smaller the cross section deformation degree is. These results are similar to those of the NC bending for TA18 tube [9], but the effects of the mandrel diameter on cross section deformation are more obvious in this work. And the peak of 2169 tube deflects toward the bending plane as mandrel diameter increases, which is different from that of the NC bending for TA18 tube [9]. The maximum cross section deformation degree with mandrel diameter of 5.23 mm is more than 4.2%, while the maximum cross section deformation degree with mandrel diameter of 5.43 mm is less than 1.8%. Although the difference between the two diameters is only 0.2 mm, the difference of the cross section deformation degree is 2.4%. So, it can be concluded that the large mandrel diameter can support the inside wall of tube more effectively to improve cross section deformation.

4.3. Effect of Mandrel Extension Length on Cross Section Quality. The mandrel extension length is an important parameter in the tube bending processes. Wrinkling may occur when the mandrel extension length is too small, while the outside of the tube may crack with overlarge mandrel extension length. In this paper, the bending processes with the mandrel extension lengths of 0 mm, 1 mm, and 2 mm have been simulated, respectively. The bulb mandrel is used, and the diameter is 5.43 mm. In the simulation, it is found that the wrinkling or cracking does not occur in all cases.

Figure 9(a) shows the tube wall thinning degree with various mandrel extension lengths. It is found that the larger the mandrel extension length, the more serious the wall thinning degree. These results are similar to those of the NC bending for TA18 and 5052O tubes [9, 17], but when the bending angle reaches the critical value, the wall thinning is of a platform deforming characteristic with little change, which differ from those of the NC bending for 5052O alloy thin-walled tube [17]. When the length is 0 mm, the maximum wall thinning degree is 9.5%; when the length is 1 mm, the maximum wall thinning degree is 10.7%; and when the length is 2 mm, the maximum wall thinning degree is 13.6%. It is because that larger mandrel extension length increases the friction between the mandrel front-end and inside wall of tube to prevent the material from flowing, which leads to tangent strain and wall thinning degree increasing. Overlarge length may cause hump, overthinning, or even cracking.

In order to avoid over-thinning, appropriate mandrel extension length should be chosen in the bending processes. A formula to calculate the maximum mandrel extension length is put forward in [3]:

$$e_{\max} = \sqrt{2\left(R + \frac{D_1}{2}\right)z - z^2}, \qquad z = D_1 - d, \tag{4}$$

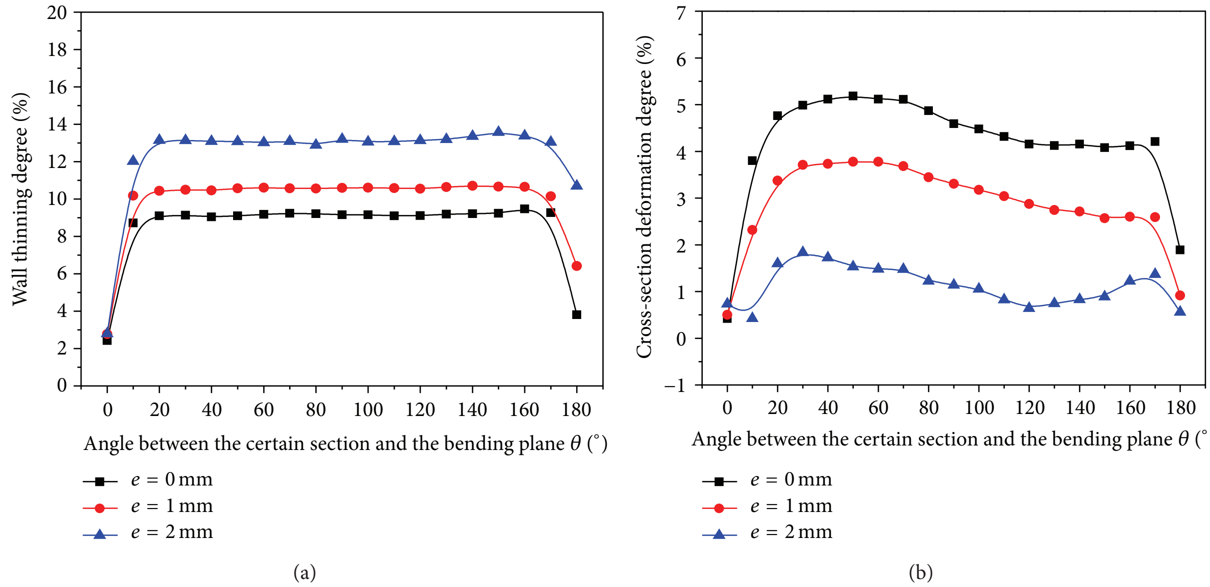


FIGURE 9: Effect of mandrel extension length on cross section quality: (a) wall thinning; (b) cross section deformation.

where D_1 is the inner diameter of the tube; R is the centerline bending radius; d is the mandrel diameter; and z is the clearance between inside wall of tube and mandrel.

In practical production, because of the tubes with relatively low elongation percentage, testing bending after calculating mandrel extension length by the equation is needed. Otherwise, hump or cracking may easily occur. In this paper, the calculated value of the maximum mandrel extension length is 2.1 mm, which is in agreement with the simulation conditions.

Figure 9(b) shows the cross section deformation degree with different mandrel extension lengths. It can be seen from Figure 9(b) that the cross section deformation of bending tube decreases with the increase of the mandrel extension length, which is similar to that of the NC bending for TA18 tube [9]. When the length is 0 mm, the maximum cross section deformation degree is 5.2%; when the length is 1 mm, the maximum cross section deformation degree is 3.8%; and when the length is 2 mm, the maximum cross section deformation degree is 1.8%. It is because that the sections are supported more effectively, which causes the inside wall of tube to undergo larger pressure stress from mandrel.

4.4. Selection of Reasonable Mandrel Parameters. According to the different usage of the bent tube, the requirements on the section quality are different. In practical production, except that the wall thinning and the cross section deformation must satisfy the requirements, the cost of production should be minimized. In the aviation technical standards, the requirements on section quality is that wall thinning degree does not exceed 25% and cross section deformation degree does not exceed 5% for high-pressure hydraulic tube. In order to gain qualified high-pressure 2169 stainless steel bent tube with diameter of 6.35 mm, wall thickness of 0.41 mm, and bending radius of 19.05 mm, the bulb mandrel and the diameter of 5.43 mm should be selected and the mandrel extension length should be set as 2 mm according to the above research results.

5. Conclusions

(1) The 3D elastic-plastic finite element model of NC bending process of 2169 stainless steel tube with small diameter is established based on the platform of ABAQUS/Explicit, the key technological problems are solved, and its reliability is validated.

(2) The mandrel type has a significant effect on cross section quality during tube NC bending. The wall thinning or cross section deformation is serious at the middle part and small in the vicinity of the bending plane or initial bending plane. The maximum wall thinning without mandrel is 6.94%, while the maximum wall thinning with cylinder mandrel or bulb mandrel is 12.1%, 13.6%, respectively. When the mandrel is not used, the section, located at the angle of 50° with the bending plane, distorts most seriously and its cross section deformation degree is about 10.9%, which exceeds the requirement of the aerial standard. When the cylinder mandrel or bulb mandrel is used, the section, located at the angle of 30° with the bending plane, distorts most seriously and its cross section deformation degree is about 3%, 1.8%, respectively, which satisfies the requirement of the aerial standard. Therefore, taking both thinning and cross section deformation into consideration, the bulb mandrel was chosen properly in this paper.

(3) The mandrel parameters have a great influence on the cross section quality of the bent tube. The larger the mandrel diameter or the mandrel extension length is, the larger the wall thinning degree of bent tube is. The larger mandrel diameter or the mandrel extension

length is, the smaller the cross section deformation is. Overlarge mandrel extension length may cause hump, overthinning, or even cracking.

(4) In order to gain qualified high-pressure 2169 stainless steel bent tube with diameter of 6.35 mm, wall thickness of 0.41 mm, and bending radius of 19.05 mm, the bulb mandrel and the diameter of 5.43 mm should be selected and the mandrel extension length should be set as 2 mm.

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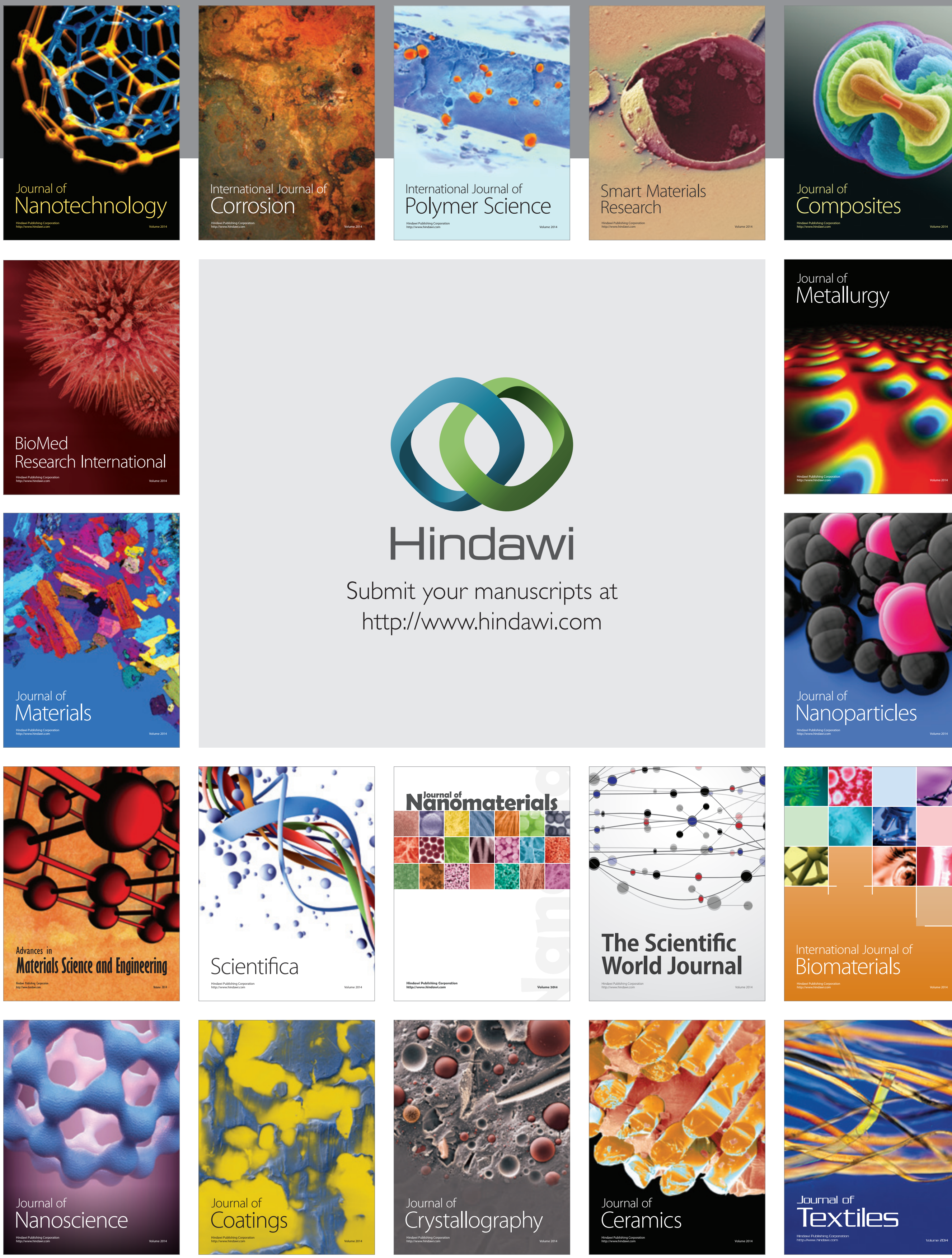
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