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Deformation behaviors of 21-6-9 stainless steel tube numerical control bending under different friction conditions

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Abstract: For contact dominated numerical control (NC) bending process of tube, the effect of friction on bending deformation behaviors should be focused on to achieve precision bending forming. A three dimensional (3D) elastic-plastic finite element (FE) model of NC bending process was established under ABAQUS/Explicit platform, and its reliability was validated by the experiment. Then, numerical study on bending deformation behaviors under different frictions between tube and various dies was explored from multiple aspects such as wrinkling, wall thickness change and cross section deformation. The results show that the large friction of wiper die−tube reduces the wrinkling wave ratio η and cross section deformation degree ΔD and increases the wall thinning degree Δt. The large friction of mandrel−tube causes large η, Δt and ΔD, and the onset of wrinkling near clamp die. The large friction of pressure die−tube reduces Δt and ΔD, and the friction on this interface has little effect on η. The large friction of bending die−tube reduces η and ΔD, and the friction on this interface has little effect on Δt. The reasonable friction coefficients on wiper die−tube, mandrel−tube, pressure die−tube and bending die−tube of 21-6-9 (0Cr21Ni6Mn9N) stainless steel tube in NC bending are 0.05−0.15, 0.05−0.15, 0.25−0.35 and 0.25−0.35, respectively. The results can provide a guideline for applying the friction conditions to establish the robust bending environment for stable and precise bending deformation of tube bending.

Key words: 21-6-9 stainless steel tube; friction; deformation behaviors; numerical control bending; finite element simulation

1 Introduction

Nowadays, the application of 21-6-9 (0Cr21Ni6Mn9N) stainless steel bent tube parts in aerospace, aviation, automobile, shipbuilding and related high technology industries becomes increasingly wide because of their advantages of high pressure resistance, high corrosion resistance and good oxidation resistance (AMS 5561G), which can satisfy the developing demands of light weight, high strength, low consuming and impact energy absorption [1]. The rapid development of the above industries has been urgently requiring the study and development of advanced plastic forming technology to bend high-quality tube parts. Among the various bending processes such as compress bending, stretch bending, rolling bending and push bending, the numerical control (NC) bending process, based on a rotary draw bending method, has become an advanced technology satisfying this requirement due to its many unique advantages such as high precision, high efficiency, digitalization, intellectualization, process stability, and mass production [2].

However, the NC bending is a multi-factor coupling physical process with tri-nonlinearity and multiple defects such as wrinkling, wall thinning and cross section deformation with the inappropriate forming parameters applied. Compared with other bending methods, NC bending is a contact dominant process under multi-die constraints including bending die, clamp die, pressure die, wiper die and mandrel. Only under precision coordination of various dies may the stable and precision bending forming process be accomplished, viz., free wrinkling, allowed wall thinning degree and cross section deformation degree. As one of major factors affecting the contact conditions, the friction between various dies and tube has a significant effect on the bending deformation behaviors of tube NC bending, and the effect is very complicated because of many tube−die interfaces. Thus, it is necessary to study the effect of friction on tube bending deformation behaviors.

Over the years, many scholars have studied tube bending deformation behaviors by using analytical, experimental or numerical methods. By theory analysis, TANG [3] derived the formulas for wall thickness change, cross section deformation, deviation of the

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neutral axis based on plastic deformation theories. WANG and AGARWAL [4] developed the analytical models to predict cross section deformation and wall thickness change of tube under axial force and internal pressure. PAN and STELSON [5] used energy methods to solve the cross section deformation and wall thickness change of plastically deformed tubes. WANG and CAO [6] researched wrinkling in tube bending with boundary restrictions at the ends, and they used an energy method to determine bending radius as a function of tube geometry, die geometry, and material properties. LI et al [7] developed an energy-based wrinkling prediction model for thin walled tube bending by applying the energy principle, combined with analytical and finite element (FE) method. YANG and LIN [8] presented a wrinkling wave function and developed a simplified wrinkling prediction model to predict the minimum bending radius for tube bending based on thin-shell theory, forming theory, energy principle and wave function. However, the analytical results are far from the experimental ones since the friction conditions on various interfaces are difficult to be considered in theory formulas.

By FE and experimental analysis, FANG et al [9−10] revealed the influence laws of mandrel types, mandrel parameters, geometry parameters and material parameters on wall thinning and cross section deformation during NC bending of 21-6-9 stainless steel tube. ZHAN et al [11−12] studied the wall thickness variation and cross section deformation under various operating parameters, mandrel parameters and different die sets for the NC bending of TA18 tubes. LI et al [13−17] researched the deformation behaviors (wrinkling, wall thinning and cross section deformation) of thin-walled stainless steel or aluminum alloy tube in rotary draw bending under different bending conditions, including the push assistant loading conditions [13], different clearances between tube and dies [14], various bending specifications [15], and the bending for the tube with large diameter and/or small bending radius [16−17]. JIANG et al [18] obtained the laws of wall thickness change and cross section deformation in NC bending of medium-strength TA18 high pressure tubes with different bending radii. YANG et al [19−20] explored the effect of the friction on bending behaviors of thin-walled tube in rotary draw bending and proposed an optimal strategy to apply the tribological conditions. Also, by FE and experimental analysis, YANG et al [21] studied wrinkling characteristics in NC bending of aluminum alloy thin-walled tubes with large diameters under multi-die constraints based on 3D elastic-plastic FE model and a wrinkling energy prediction model. By experimental analysis, the effect of geometric parameters and process parameters on wall thickness change and cross section deformation of thin-walled tube NC bending were investigated [22−24]. While up to now, limited efforts have been reported to explore the role of friction conditions in bending deformation behaviors of tube NC bending in terms of multiple defects [19−20]. Due to lack of knowledge on bending deformation behaviors under different friction conditions, the forming quality or forming limit in NC bending can not be further improved and the “trial and error” method is still mainly used to optionally select lubricants with inferior repeatability, which causes rapidly increased cost and time and decreased NC machine’s efficiency and precision.

Thus, in this work, a 3D elastic plastic FE model of the tube NC bending process was established under ABAQUS/Explicit environment. Then, a systematical study on friction effects on bending deformation behaviors of different interfaces was concerned with respect to three major defects, i.e. wrinkling, wall thickness change and cross section deformation. The results of this work are useful to select reasonable friction conditions in tube NC bending process, and FE simulation method can be used to study the effect of other parameters on the forming quality and forming limit of tube NC bending process.

2 Friction characteristics and forming indices for tube NC bending

2.1 Friction characteristics for tube NC bending

During NC bending process, as shown in Fig. 1, the pressure force N_c is applied to the front end tube by the insert die (tied with bending die) and clamp die, which introduces enough friction force f_c to drag the tube past the tangent point and rotates along the bending die groove to obtain the desired bending angle and bending radius R. Pressure die applies enough pressure force N_p to the half outer surface of tube against wiper die, which provides bending moment and exerts the forward friction f_p to the tube to help to push the materials into bending deformation regions. The forward friction f_p decreases the tensile stress and makes the strain neutral layer shift outwards. Besides the above basic dies for tube bending, both the wiper die and mandrel are applied to exert normal forces N_w and N_m to prevent wrinkling and to decrease cross section deformation, while they induce fiction forces f_w and f_m with contrary direction to the flow direction of tube materials.

Therefore, the tube NC bending essentially depends on the contact conditions between tube and various dies, which may change the stress and strain distribution in local field or the whole deformation zones. In summary, there are five kinds of interfaces involved in tube bending including mandrel−tube, wiper die−tube, bending

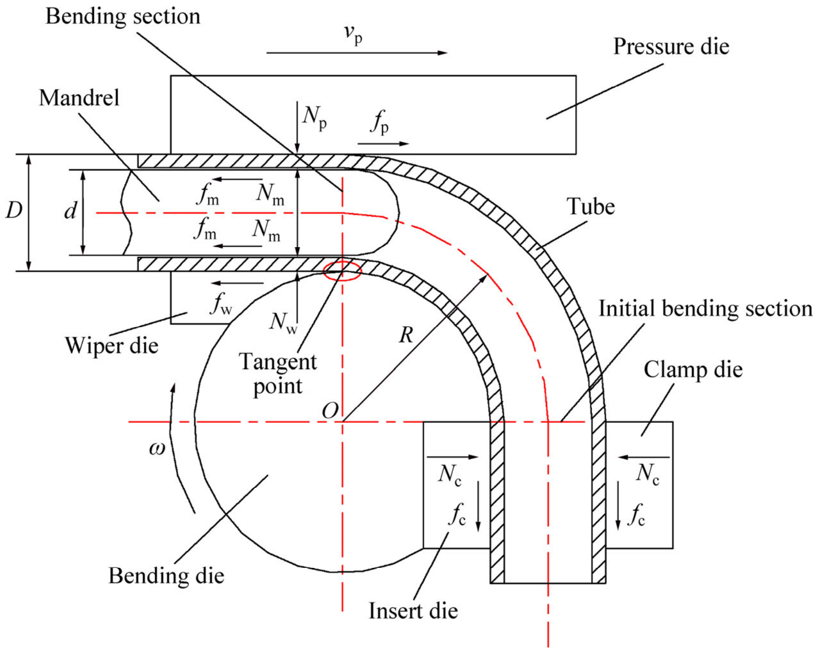

Fig. 1 Schematic diagram of tube NC bending

die−tube, pressure die−tube and clamp die−tube. Based on the above analysis, except for clamp die−tube interface, there is finite relative slip between tube and dies. Thus, the friction types on these interfaces can be known as kinetic ones. Also, the local progressive bending characteristics in NC bending process result in almost constant contact zones on fiction interface [17].

2.2 Forming indices for tube NC bending

Some indices are available to evaluate the tube bending deformation correspondingly.

The bending instabilities can be qualitatively described by the wrinkling wave ratio η as [25]

$$\eta = \frac{D_1 - D_2}{2D} \times 100\% \tag{1}$$

where D_1 is the maximum section length between the wave crest of the intrados and extrados of tube, D_2 is the minimum section length between the wave crest of the intrados and the extrados, and D is the initial tube outer diameter as shown in Fig. 2(a). Large η means increased wrinkling tendency.

The wall thickness change (wall thinning and thickening) degree Δt can be represented as

$$\Delta t = \left| \frac{t - t'}{t} \right| \times 100\% \tag{2}$$

where t is the initial wall thickness of tube, and t' is the minimum or maximum wall thickness after bending deformation as shown in Fig. 2(b).

Due to the special boundary constraints in NC bending as shown in Fig. 2(b), the tube is constrained in the transverse direction by the groove of bending die and under free deformation conditions in vertical direction. Thus, the change ratio of the cross section along vertical direction is chosen to express the cross section deformation degree ΔD as

$$\Delta D = \frac{D - D'}{D} \times 100\% \tag{3}$$

where D is the initial tube outer diameter, and D' is the vertical length of cross section after bending deformation as shown in Fig. 2(b).

The larger the indices, the worse the bending quality. It is noted that the tolerances are different for specific applications. Given the high-pressure safety requirements of aircrafts, the wrinkling wave ratio, wall thinning degree and cross section deformation degree should be less than 2%, 25% and 5%, respectively.

3 Development and evaluation of 3D elastic-plastic FE model for tube NC bending

3.1 3D elastic-plastic FE model

Compared with the static implicit algorithm (Quasi-Newton integration method), the dynamic explicit algorithm (central difference algorithm) was well-suited to simulate 3D metal plastic forming process because of the unique advantages such as little solution costs, few difficulties in dealing with dynamic contact conditions and large deformation/rotation process, and also ability of predicting nonlinear responses such as wrinkling, wall thickness change and cross section deformation without iteration or convergence tolerance. Based on previous studies [9−10] and according to the practical tube bending process, a 3D elastic-plastic FE model was established to simulate 21-6-9 stainless steel tube NC bending process under FE platform ABAQUS/Explicit, as shown in Fig. 3.

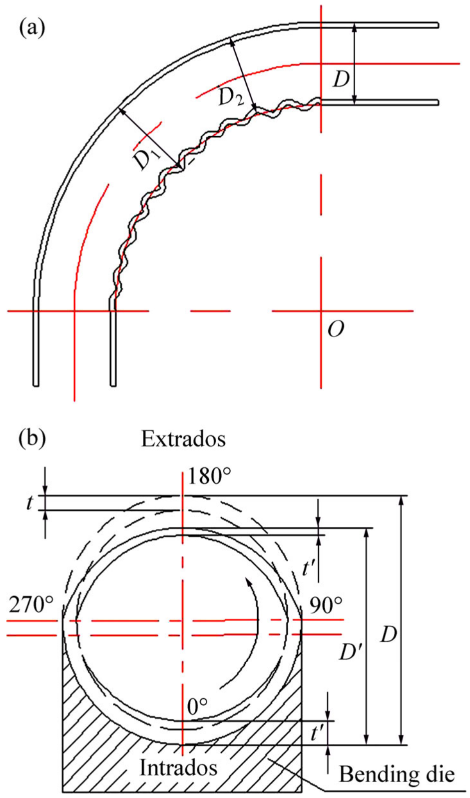

Fig. 2 Schematic of defect measurement: (a) Wrinkling; (b) Wall thickness change and cross section deformation

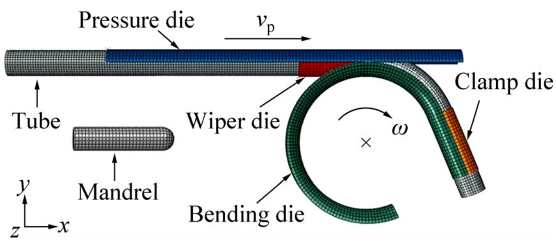

Fig. 3 3D elastic-plastic FE model for 21-6-9 stainless steel tube NC bending

Due to plane stress assumption, the four-node doubly curved thin shell S4R was used to model the tube with the following features: reduced integration and hourglass control. Five integration points with Simpson integration rule were used through the tube wall thickness to describe the tube bending deformation better. The relatively rigid dies were modeled as discrete rigid bodies with four-node 3D bilinear quadrilateral rigid element R3D4. The element size of 1.5 mm×1.5 mm was used to obtain the tradeoff between "computational accuracy" and "computational efficiency". The mass scaling factor of 2000 was utilized to improve the computation cost with neglected inertial effect of explicit FE simulation by using the convergence analysis.

The strain hardening characteristics were described by the Ludwigson model $\bar{\sigma} = K\bar{\varepsilon}^n + \mathrm{e}^{(a-b\bar{\varepsilon})}$ and the von Miss yield criterion was used to describe tube material's yield behaviors. Table 1 lists the mechanical properties of the 21-6-9 stainless steel tube materials obtained by the uniaxial tension test according to the GB/T228.1−2010 [26]. The value of equivalent strain during bending process is more than the maximum value of equivalent strain obtained by the tension test, thus the remaining part of the flow curve is extrapolated for the FE simulation.

Table 1 Mechanical properties of 21-6-9 stainless steel tube

Material parameter	Value
Elastic modulus, E/GPa	193
Poisson ratio, v	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
a	5.7
b	27.4

The boundary constrains and loading paths were applied by two approaches to realize the practical process of NC bending: "displacement/rotation" and "velocity/angular velocity". Both bending die and clamp die were constrained to rotate along the global z-axis simultaneously, while the pressure die was 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 was constrained along all degrees of freedom. The speed of mandrel was kept stationary along the global x-axis during tube bending process. After the bending process was finished, the mandrel would be retracted along the global x-axis. The smooth step amplitude curves were used to define the smooth loading process of bending die, clamp die, pressure die and mandrel to ensure neglected inertial effects in explicit simulation of the quasi-static process.

The Coulomb friction law was selected to represent the friction behaviors between tube and various dies. According to Ref. [27], the twist compression test was chosen to reproduce the friction conditions of NC bending and evaluate the friction coefficients for various tribological conditions, and the reference friction coefficients on different interfaces for 21-6-9 stainless steel tube NC bending are listed in Table 2. The large friction coefficient should be assigned to the clamp die−tube interface to reduce or avoid the relative slip at this contact interface. In ABAQUS, so-called "rough"

Table 2 Friction coefficients in various contact interfaces

Contact interface	Friction coefficient
Tube−bending die	0.1
Tube−pressure die	0.25
Tube−clamp die	∞
Tube−wiper die	0.05
Tube−mandrel	0.05

friction with infinite coefficient was used to satisfy no relative slip conditions at all.

The "surface-to-surface contact" method was used to define the contact conditions between tube and various dies, which was allowed to slide between these surfaces. The "kinematic constraints" method was used to describe mechanical constraints for contact pairs. For contact interface of mandrel−tube, it was simulated with "penalty method". Moreover, according to the actual conditions, the sliding formulation for every contact interface was the "finite sliding" except the one for clamp die−tube contact pair with the "small sliding", namely, not being allowed to slide between clamp die and tube.

3.2 Evaluation of established FE model

In order to evaluate the 3D elastic-plastic FE model, the experiments were carried out by the NC tube bender WFCNC-16. The forming parameters are listed in Table 3. The wall thickness of the bent tubes was measured by a micrometer screw gauge, and the cross section deformation of the bent tubes was measured by a vernier caliper.

Table 3 Forming parameters for 21-6-9 stainless steel tube NC bending

Parameters	Value
Diameter, D/mm	15.88
Wall thickness, t/mm	0.84
Bending speed, ω/(rad·s^{-1})	0.4
Assistant pushing speed, V_p/(mm·s^{-1})	19.056
Bending angle, θ/(°)	180
Bending radius, R/mm	47.64
Mandrel extension length/mm	3.5
Clearance of mandrel−tube/mm	0.05
Clearance of other dies−tube/mm	0.1

Figure 4 shows the comparison between FE simulation and experiments in terms of wall thinning degree Δt and cross section deformation degree ΔD. It can be seen that the FE simulation results have a good agreement with the experimental ones, and the errors of the maximum wall thinning degree and maximum cross section deformation degree are 3.98% and 2.02%, respectively. Thus, the results show that the FE model used in the work is credible, which can be used to further explore the friction role in bending deformation of 21-6-9 stainless steel tube NC bending.

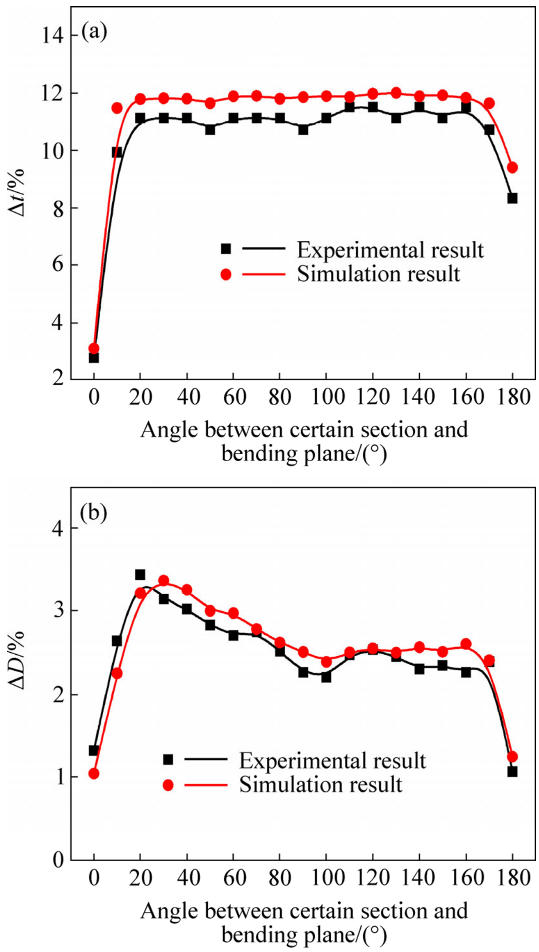

Fig. 4 Comparison of simulation results with experimental ones: (a) Wall thinning degree; (b) Cross section deformation degree

4 Results and discussion

The effect of friction on deformation behaviors of 21-6-9 stainless steel tube in NC bending was studied from several aspects such as wrinkling, wall thickness change and cross section deformation.

The premise of tube NC bending is that there is no relative slip between clamp die and tube. So, the necessary tribological condition for stable tube bending deformation is obtained, namely, tough dry friction should be used to clamp die−tube contact pair to firmly drag the tube past the tangent point. Thus, numerical study on the influence of friction on deformation behaviors of other interfaces such as wiper die−tube, mandrel−tube, pressure die−tube and bending die−tube could be carried out by changing the friction coefficient from 0.05 to 0.5, while the other friction coefficients are employed as listed in Table 2. The forming parameters are listed in Table 3.

4.1 Effect of friction on wrinkling instability

4.1.1 Effect of friction between wiper die and tube

Figure 5 shows the effect of friction coefficient between wiper die and tube (μ_w) on wrinkling wave ratio (η). Wrinkling does not happen on different friction conditions at wiper die−tube. It can be seen form Fig. 5 that the wrinkling wave ratio decreases with the increase of friction coefficient on this interface, which indicates that the larger friction on wiper die−tube helps to decrease the wrinkling tendency. The reason is that, the larger the friction is, the smaller the tangent compression stress is, resulting in the decrease of wrinkling tendency. Moreover, the wall thickening degree decreases with large friction coefficient on this interface, as shown in Fig. 6. It is indicated that, the larger friction coefficient makes the material flow behind wiper die blocked by the friction force and the increased drag force of wiper die results in relative slip between clamp die and tube, which causes the wrinkling to start near clamp die. Also, the larger friction on this interface leads to the wear of wiper die. So, taking into account the little importance of friction effect on wrinkling start, the friction coefficient on wiper die−tube surface should not be large.

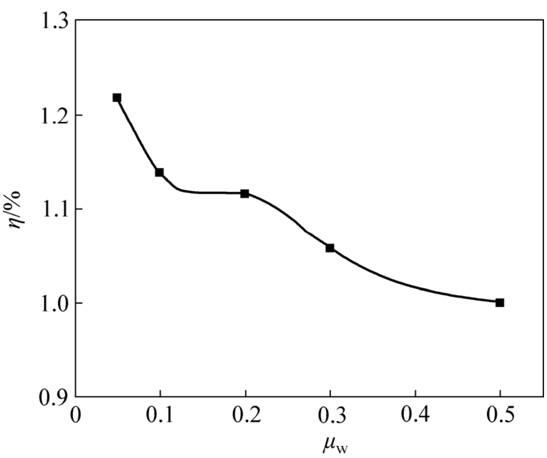

Fig. 5 Effect of μ_w on wrinkling wave ratio

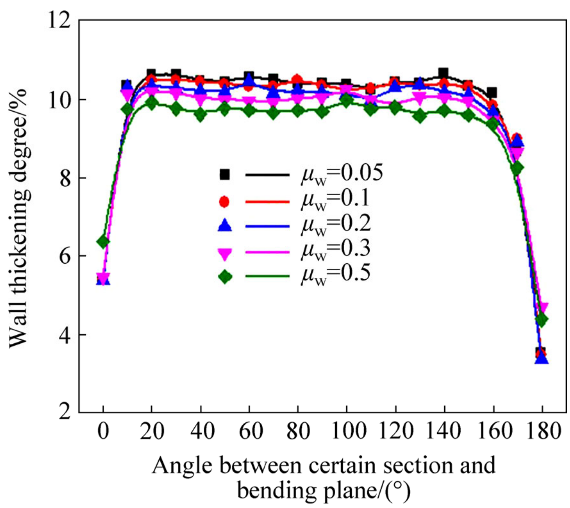

Fig. 6 Effect of μ_w on wall thickening degree

4.1.2 Effect of friction between mandrel and tube

Figure 7 shows the effect of friction coefficient between mandrel and tube (μ_m) on wrinkling wave ratio (η). It is found that the wrinkling wave ratio increases with the increase of friction coefficient on this interface. The wrinkling does not happen when the friction coefficient on mandrel−tube interface is less than 0.3. When the friction coefficient is more than 0.3, the wrinkling happens near clamp die and the waves become more serious with the larger friction coefficient, because the larger friction force between mandrel and tube is, the larger the drag force exerted by mandrel-tube is, which prevents materials from flowing forward and leads to relative slip between clamp die and tube. The larger the friction coefficient is, the larger the relative slip distance is, which causes the wrinkling near clamp die. At the same time, with larger friction coefficient, the tube materials can not be dragged past the tangent point efficiently, and the excessive materials are piled up behind the wiper die, which leads to the local wrinkling near the tangent point. The above comprehensive effects make the wrinkling tendency more serious. And also the larger friction in the mandrel−tube interface aggravates the wear of the die and causes the scratch of the tube surface.

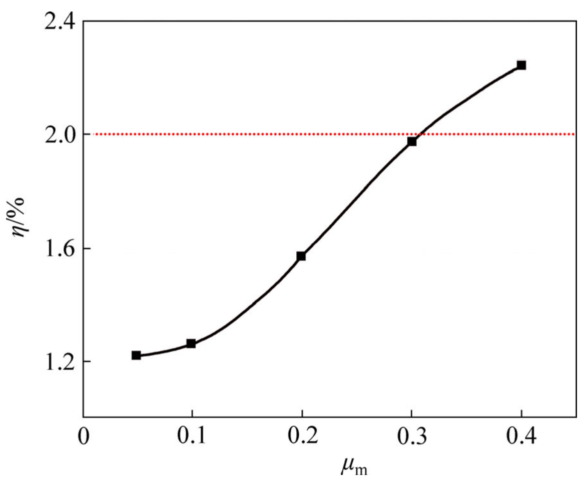

Fig. 7 Effect of μ_m on wrinkling wave ratio

4.1.3 Effect of friction between pressure die and tube

Figure 8 shows the effect of friction coefficient between pressure die and tube (μ_p) on wrinkling wave ratio (η). It is discovered that the wrinkling does not happen under different friction conditions and the wrinkling wave ratio changes slightly with increasing friction coefficient, which differs from that of the NC bending for 5052O alloy thin-walled tube under small bending radii [20]. This is because the pressure die contacts with the outer side of tube, which makes the acting force of pressure die difficult to transfer from the outer side of tube to the inner side. Thus, the friction has hardly any effect on wrinkling. Also it can be seen from

Fig. 9 that the wall thickening degree has hardly changed under various friction coefficients, which further testifies the above results.

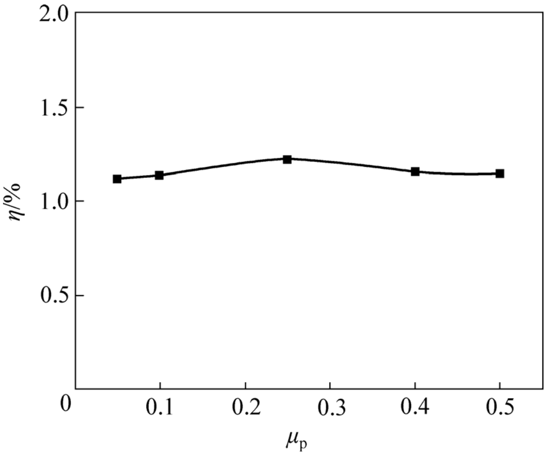

Fig. 8 Effect of μ_p on wrinkling wave ratio

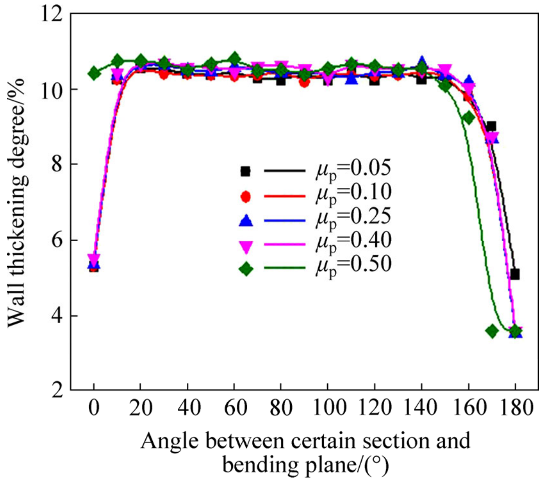

Fig. 9 Effect of μ_p on wall thickening degree

4.1.4 Effect of friction between bending die and tube

Figure 10 shows the effect of friction coefficient between bending die and tube (μ_b) on wrinkling wave ratio (η). It is found that the wrinkling does not occur under different friction conditions and the wrinkling

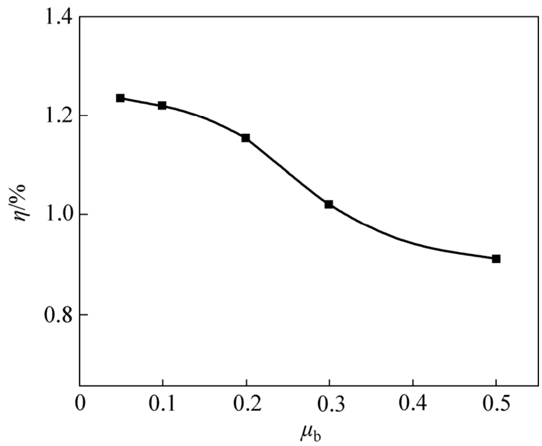

Fig. 10 Effect of μ_b on wrinkling wave ratio

wave ratio decreases with larger friction coefficient on this interface. The results are different from those of NC bending for 5052O alloy thin-walled tube under small bending radii [20]. The reason is that the larger the friction coefficient is, the smaller the tangent compression stress is. Thus, the wrinkling tendency decreases. Also, it is found that the larger friction coefficient causes smaller wall thickening, which further proves the above conclusion, as shown in Fig. 11.

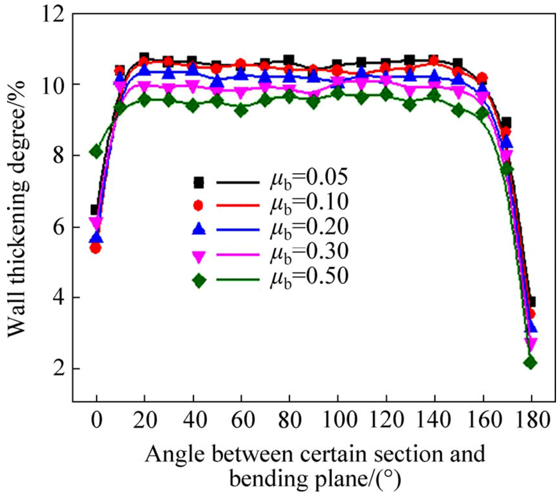

Fig. 11 Effect of μ_b on wall thickening degree

4.2 Effect of friction on wall thinning and cross section deformation

4.2.1 Effect of friction between wiper die and tube

Figure 12 shows the effect of friction coefficient between wiper die and tube (μ_w) on wall thinning degree (Δt) and cross section deformation degree (ΔD). It can be seen from Fig. 12(a) that the wall thinning degree increases with increasing friction coefficient on wiper die−tube interface. But the increasing of the wall thinning degree is not obvious. This is because with larger friction coefficient on this interface, the tangent tensile stress at the outer side increases, which causes the increase of wall thinning degree.

Figure 12(b) shows that, the cross section deformation degree reduces with the increase of friction coefficient. But the decrease of the trend is not obvious. These results are different form those of the NC bending for 5052O alloy thin-walled tube [19−20]. The reasons are that, firstly, the larger friction coefficient leads to the increase of the tangent tensile stress, which causes the cross section deformation degree to increase; secondly, as mentioned in Section 4.1.1, the lager friction on this interface causes the materials accumulation near the bending section and the wrinkling near clamp die, which leads to the decrease of cross section deformation. The comprehensive effects above make the cross section deformation degree decrease with the increase of friction coefficient.

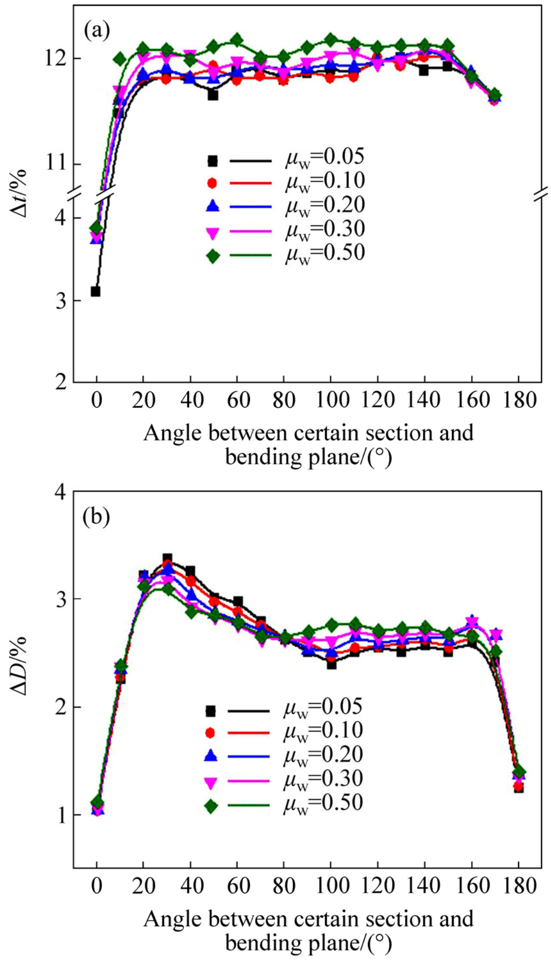

Fig. 12 Effect of μ_w on wall thinning degree (a) and cross section deformation degree (b)

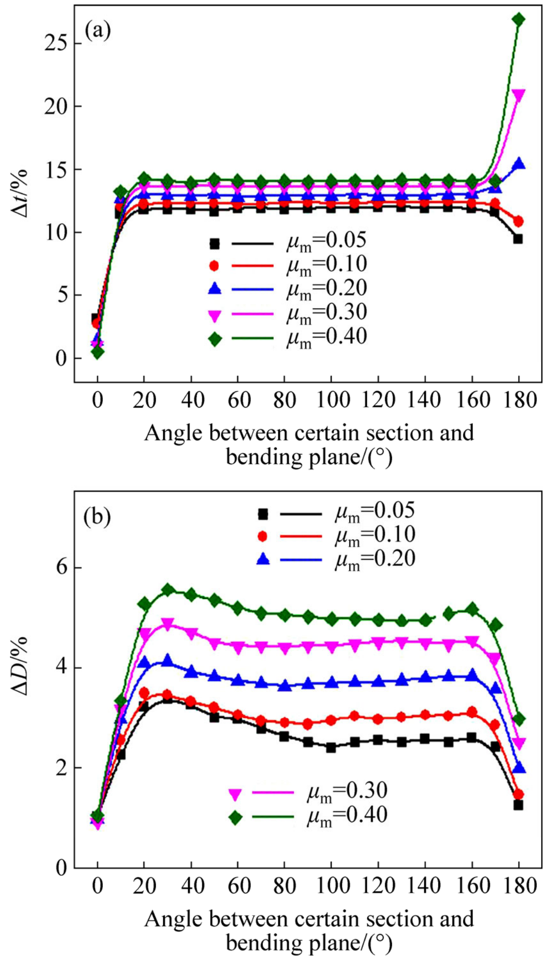

Fig. 13 Effect of μ_m on wall thinning degree (a) and cross section deformation degree (b)

4.2.2 Effect of friction between mandrel and tube

Figure 13 shows the effect of friction coefficient between mandrel and tube (μ_m) on wall thinning degree (Δt) and cross section deformation degree (ΔD). It can be seen that the larger friction on mandrel−tube interface leads to more serious wall thinning and cross section deformation, because the larger the friction coefficient on this interface is, the larger the tangent tensile stress at the extrados is, which causes more serious wall thinning and cross section deformation. Also, it can be seen from Fig. 13(a) that when the friction coefficient on this interface is more than 0.2, the wall thinning degree increases sharply at initial bending section. The main reason is that, the larger the friction coefficient on this interface is, the larger the drag force exerted by mandrel−tube at the beginning is, which causes the wall thinning to become larger abruptly at the initial bending section. Moreover, as mentioned in Section 4.1.2, the large friction coefficient between mandrel and tube interface causes the onset of wrinkling, which may enhance the wall thinning degree.

4.2.3 Effect of friction between pressure die and tube

Figure 14 shows the effect of friction coefficient between pressure die and tube (μ_p) on wall thinning degree (Δt) and cross section deformation degree (ΔD). It is found that the larger friction coefficient on this interface helps to reduce both the wall thinning degree and cross section deformation degree. These results are similar to those of the NC bending for 5052O alloy thin-walled tube with small bending radii [20], but the effects of friction on wall thinning and cross section deformation are less obvious in this work. The reason is that the larger friction on this interface improves the pushing assistant role of pressure die. The larger friction force decreases the tangent tensile stress at the outer side and helps to push more materials into plastic bending areas. But because of the characteristic of the sliding friction, and the contact areas of the pressure die and tube reducing with the bending process conducting, the effects of friction on this interface on wall thinning and cross section deformation are less evident.

4.2.4 Effect of friction between bending die-tube

Figure 15 shows the effect of friction coefficient between bending die and tube (μ_b) on wall thinning degree (Δt) and cross section deformation degree (ΔD). It is found that the friction coefficient on this interface has

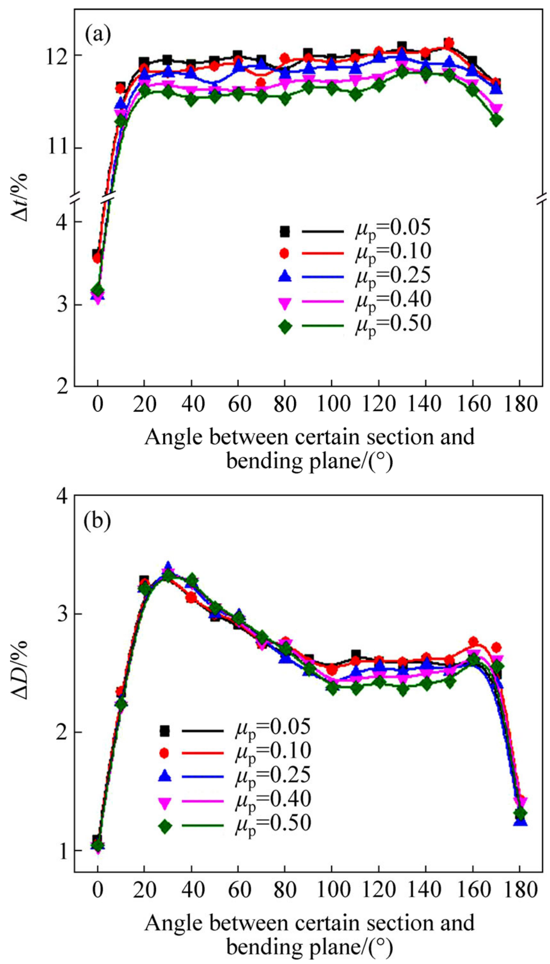

Fig. 14 Effect of μ_p on wall thinning degree (a) and cross section deformation degree (b)

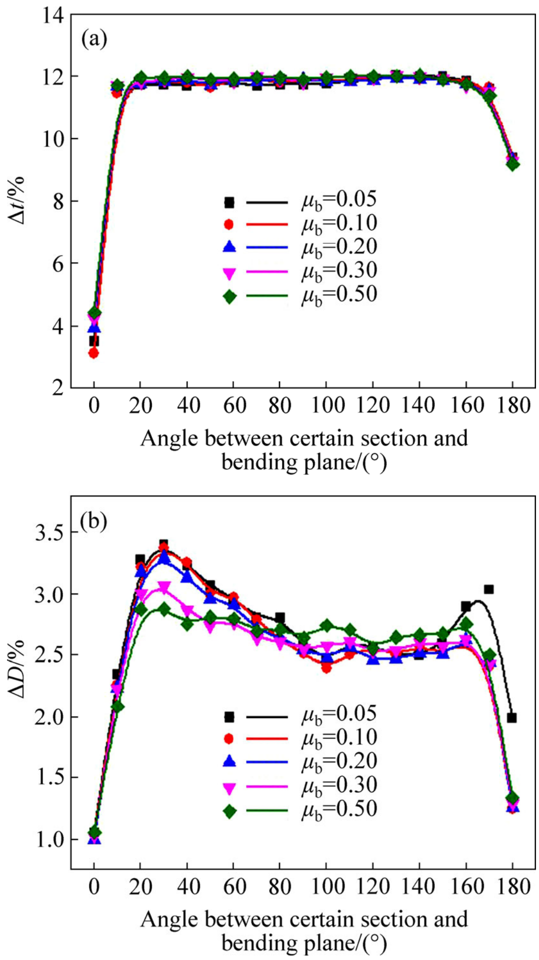

Fig. 15 Effect of μ_b on wall thinning degree (a) and cross section deformation degree (b)

little effect on the wall thinning at the extrados, while the larger friction coefficient on this interface decreases the cross section deformation degree. The main reason is that the bending die does not contact directly with the outer side of the tube, which makes the acting force of bending die difficult to transfer from the inner side of tube to the outer side. Thus, the friction has hardly any effect on wall thinning. However, the increase of friction between bending die and tube decreases the tangent compression stress, which causes the decrease of the cross section deformation degree.

4.3 Selection of reasonable friction conditions in 21-6-9 stainless steel tube NC bending

Based on the above analysis, it is shown that by applying the reasonable friction conditions on four different interfaces considering the interactive effects of friction on bending deformation behaviors, the multiple defects can be avoided or alleviated. Thus, based on the understanding of the friction role in tube NC bending, the reasonable friction conditions are chosen to ensure the stable bending forming and obtain the precise bending parts. The detailed discussion is as follows.

The large friction of wiper die−tube reduces the wrinkling wave ratio (η) and cross section deformation degree (ΔD), and increases the wall thinning degree (Δt). However, the effects of friction on η, ΔD and Δt are not significant. In addition, the wiper die is a vulnerable part with very thin feather edge during bending process. Thus, considering little friction effect on wrinkling, wall thinning and cross section deformation, the wiper die−tube interface should be lubricated with a little oil to avoid wear and to extend the life of wiper die in actual production. The reasonable friction coefficient on this interface should be 0.05−0.15.

The small friction of mandrel−tube can reduce η, ΔD and Δt effectively, thus the friction on mandrel−tube should be as small as possible. The reasonable friction coefficient on this interface should be 0.05−0.15. To reduce the friction on this interface, enough lubricant should be evenly daubed to the inside tube and mandrel surface in actual production.

The large friction should be applied to the interface of pressure die−tube. The large friction on this interface can reduce Δt and ΔD, and the effect of friction on η is not obvious. But the friction on this interface should not be increased too much. The reason is that too much friction on this interface leads to the tube outside surface to be scratched. The reasonable friction coefficient on this interface should be 0.25−0.35. Generally, dry friction condition satisfies the requirements of the stable bending without scratching tube outside surface in actual production.

The large friction of the interface between bending die and tube can reduce η and ΔD, and the friction on this interface has little effect on Δt. The reasonable friction coefficient on bending die−tube interface should be 0.25−0.35. Dry friction condition is also used to this interface in actual production to satisfy the requirements of the stable bending without scratching tube outside surface.

5 Conclusions

1) With larger friction of wiper die−tube, the wrinkling wave ratio and cross section deformation degree reduce, while the wall thinning degree increases.

2) With larger friction of mandrel−tube, the wrinkling wave ratio, wall thinning degree, and cross section deformation degree increase quickly, and the larger friction on this interface blocks the materials to flow past tangent point and causes to pile up. The onset of wrinkling may enhance the wall thinning degree.

3) The larger friction on pressure die−tube interface reduces the wall thinning degree and cross section deformation degree, and the friction on this interface has little effect on wrinkling wave ratio.

4) The larger friction on bending die−tube interface can reduce the wrinkling wave ratio and cross section deformation degree, and the friction on this interface has little effect on wall thinning degree.

5) The reasonable friction coefficients on wiper die−tube, mandrel−tube, pressure die−tube and bending die−tube of 21-6-9 stainless steel tube in NC bending are 0.05−0.15, 0.05−0.15, 0.25−0.35 and 0.25−0.35, respectively.

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