Mandrel role in numerical control rotary draw bending process of TA18 high strength titanium alloy tube

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Abstract: In order to improve bent tube forming quality and limit, the reasonable mandrel parameters need to obtain during tube bending process. A three dimensional (3D) elasto-plastic finite element (FE) model of the whole process of TA18 high strength titanium alloy tube during numerical control rotary draw bending (RDB) was developed based on the FE software of ABAQUS, and its reliability was verified. Then, simulation and analysis of the mandrel role in tube numerical control RDB was carried out by using the model. The results show that the wall thinning increases and the cross section distortion decreases with increasing of mandrel extension length or mandrel diameter. The optimal range of the mandrel extension length and mandrel diameter is 0.5mm-1.5mm and 5.2372mm-5.3872mm, respectively.

1. Introduction
TA18 high strength titanium alloy tubes have attracted increasing applications in hydraulic tubing systems for advanced aircraft and engine because of low density, high strength-to-weight ratio, excellent corrosion resistance and high pressure resistance [1]. Among all kinds of tube bending methods such as roll bending, compress bending, push bending and stretch bending, the numerical control rotary draw bending (RDB) as shown in Figure1 can realize the precision and high efficiency bending forming for high strength titanium alloy tubes. Compared with aluminum alloy and stainless steel tubes, the TA18 high strength tubes are more difficult to bending forming, and the forming defects with respect to wall thinning, cross section distortion are easy to produce after bending because of its characteristic of large yield ratio and low elongation. Among many process parameters, the mandrel parameters play a significant role on enhancing forming quality and limit of tube in the RDB process. Thus, study on mandrel roles in numerical control RDB process of the TA18 high strength tubes have a significant theoretical significance and reality application value.

Over the years, many scholars have researched on wall thinning and cross section distortion in tube bending process by using theoretical, experimental and FE numerical simulation method. Lu et al.[2] presented some theoretical formulae such as the distribution of stress, cross section distortion, variation of wall thickness, bending moment and curvature radius of neutral layer based on theory of plastic deformation. Liu et al.[3] derived the analytical expression of cross section distortion of an outer flange of thin-walled 3A21 aluminum alloy rectangular tube in the RDB process based on plastic deformation theory, and the results have an important significance to improve the thin-walled rectangular bent tube forming quality. By experimental method, Tian et al.[4] researched the effect
laws of the bending angle, ball number of mandrel, extension length of mandrel, bending speed on the wall thinning of the large diameter thin-walled 6061-T4 aluminum alloy tube with 50.8 mm×0.889 mm (diameter×wall thickness) in numerical control bending process. The effects of process parameters on the wall thinning and cross section distortion of 5052O aluminum alloy thin-walled tube with large diameter during numerical control bending were experimentally investigated in Ref.[5]. Based on the FE software of ABAQUS, Fang et al.[6,7] studied the influences of friction coefficients and mandrel parameters on the wall thinning and cross section distortion of 21-6-9 high strength stainless steel tube during numerical control bending. The effects of the clearance between tube and dies and mandrel parameters on the wall thinning and cross section distortion of aluminum alloy tube or stainless steel tube during numerical control bending were researched using the FE platform of ABAQUS/Explicit by Li et al.[8,9]. In recent years, for the medium or high strength TA18 titanium alloy tubes, Jiang et al.[10] numerically researched the influences of bending radius on the wall thinning and cross section distortion behaviors of medium strength TA18 tubes in the RDB process. The influences of geometry parameters, material parameters on the wall thinning and cross section distortion of the high strength TA18 tubes in numerical control RDB process were numerically investigated in literatures [11,12].

Figure 1. Schematic diagram of tube numerical control RDB

In the previous studies, the influences of geometrical parameters, process parameters and material parameters on the wall thinning and cross section distortion of tube bending were generally conducted. However, the study on the influences of mandrel on the wall thinning and cross section distortion in tube bending are little involved. Thus, in this work, taking the TA18 high strength tube with the specification of 6.35 mm×0.4064 mm as object, a 3D elasto-plastic FE model for the whole process of the TA18 high strength tube in numerical control RDB is developed based on the FE software of ABAQUS, and its reliability is verified. Then, the influences of mandrel parameters on the wall thinning and cross section distortion of the TA18 high strength tube in numerical control RDB are revealed, and the optimal range of the mandrel parameters is obtained. The research results may help to better understanding the role of mandrel during tube numerical control RDB process.

2. FE model and its reliability validation
On the basis of the actual tube numerical control RDB process, a 3D elasto-plastic FE model for the whole process of the TA18 high strength tube numerical control RDB was developed based on the FE software of ABAQUS as shown in Figure 2. The explicit and implicit algorithms were applied to solve the bending tube and springback, respectively. The rigid dies including bending die, clamp die, pressure die, wiper die and mandrel were meshed by four-node bilinear quadrilateral rigid element R3D4. The tube was described by four-node doubly curved thin shell element S4R. Five integration points were chose across the thickness to describe the tube bending deformation better. The Hill (1948)’s anisotropic yield criterion was used to describe the deformation behaviors of the TA18 high
strength tube, and the work hardening behavior of the TA18 high strength tube was described by the power exponent equation $\sigma = K(\varepsilon + a)^n$. The coulomb friction model was employed to describe the friction contact behaviors between tube and dies. The mechanical properties of the TA18 high strength tube and friction coefficients between tube and different dies can be found in Ref.[11].

The contact behaviors between tube and dies were defined by “surface-to-surface contact” method. The boundary constraints and loading paths were used by two ways to realize the real tube numerical control RDB: “displacement/rotation” and “velocity/angular velocity”. The smooth step amplitude curves were applied to describe the smooth loading of dies except for wiper die to ensure little inertial effects in explicit FE simulation of the quasi-static process. For unloading process, all dies were removed and a fixed boundary condition was used to avoid the rigid motion.

![3D elasto-plastic FE model of the TA18 high strength tube in numerical control RDB](image)

Figure 2. 3D elasto-plastic FE model of the TA18 high strength tube in numerical control RDB

Figure 3 shows the energy curves of bending FE model. As can be seen from Figure 3 that the ratio of the kinetic energy (ALLKE) to internal energy (ALLIE) and that of the artificial strain energy (ALLAE) to internal energy (ALLIE) are less than 5% with the change of the time, which show that the FE model has no obvious dynamic effect and hourglass phenomenon. Therefore, the FE model is stable and reliable in theory, and the reasonable quasi-static solution can be obtained by using the model. The fluctuation of the energy curves in initial stage is caused by the bending loading vibration at the beginning. The experimental validation of the FE model also can be found in Ref.[11].

![Energy curves of bending FE model](image)

Figure 3. Energy curves of bending FE model

3. Results and discussion
For the hemispherical mandrel chosen in this paper, the mandrel parameters mainly include the mandrel extension length $e$ and mandrel diameter $d$ (shown in Figure 1), which are the significant dimension parameters since these greatly affect the forming quality of the bent tube. Therefore, the effects of the $e$ and $d$ on the wall thinning and cross section distortion of the TA18 high strength tube during numerical control RDB were investigated. Here, the wall thinning degree $\Delta t$ is expressed as $\Delta t = (t - t') / t$, where $t$ and $t'$ denote the initial tube wall thickness and the wall thickness after bending deformation, respectively. The cross section distortion degree $\Delta D$ is written as $\Delta D = (D - D') / D$, where $D$ and $D'$ denote the initial tube diameter and the vertical length of the cross section after bending,
respectively.

Figure 4 shows the effect of the $e$ on the wall thinning and cross section distortion of the TA18 high strength tube in numerical control RDB process. It can be seen from Figure 4(a) that the wall thinning degree increases with the increase of the $e$. These results are similar to those of the numerical control RDB of 5052O aluminum alloy tube and 2169 stainless steel tube[5,6], but when the bending angle attains the critical value, the wall thinning degree shows a platform deforming characteristic with little change, which are different from those of the RDB of the thin-wall 5052O aluminum alloy tube[5]. When the $e$ increases form 0 mm to 2mm, the maximum value of the wall thinning degree increases form 7.87% to 10.60%, which has a safe distance for the upper limit of aviation standard of 15%. The reason is that larger $e$ increases the friction force between the mandrel front-end and inside wall of tube to prevent material from flowing, which causes tangential strain and wall thinning to increase.

Form Figure 4 (a), it is found that the cross section distortion degree decreases with increasing of the $e$ when the $e$ is less than 1.5mm. The main reason is that, the support role of the mandrel to the tube is more obvious when the $e$ increases, which leads to decrease the cross section distortion degree. When the $e$ is more than 1.5mm such as 2mm, the cross section distortion degree augments sharply in the vicinity of the initial bending plane, and the value increases form 1.30% to 4.95%, which is close to the upper limit of the aviation standard of 5%. This is because that overlarge $e$ makes the bending deformation force increase and the clamp die slip [13], which lead to the cross section distortion degree increase sharply in the region near the initial bending plane. Overlarge $e$ may cause hump, over-thinning, or even cracking. To avoid hump, over-thinning, an appropriate $e$ should be selected in bending process. The calculated value of the maximum $e$ is 1.8 mm by the formula presented in literature [9], which further proves the above conclusion.

It also can be seen from Figure 4 (b), When the $e$ is 0mm, the maximum value of the cross section distortion degree is 5.47%, which exceeds the upper limit of the aviation standard of 5%. Thus, considering the influences of the $e$ on the wall thinning and cross section distortion, the range of the reasonable $e$ is 0.5 mm-1.5mm.

![Figure 4. Effect of $e$ on wall thinning and cross section distortion: (a) wall thinning degree; (b) cross section distortion degree](image)

Figure 5 shows the influence of $d$ on the wall thinning and cross section distortion of the TA18 high strength tube during numerical control RDB. The wall thinning degree augments with increasing of the $d$. These results are similar to those of the numerical control RDB of the 2169 stainless steel tube [6], but the influence of the $d$ on the wall thinning degree is less evident in this paper. The maximum value of the wall thinning degree increases from 6.50% to 8.73% when the $d$ increases form 5.0372mm to 5.4372mm as shown in Figure 5(a). It is because that increasing the $d$ makes friction force between mandrel and inside wall of tube increase, and accordingly leads to larger tangential strain and more serious wall thinning degree of bent tube.

From Figure 5(b), it can be seen that the cross section distortion degree reduces with increasing of the $d$, and the decreasing tendency slows down. These results are similar to those of the RDB of the 2169 stainless steel tube[6], but when the bending angle attains the critical value, the cross section
distortion degree shows a platform deforming characteristic with little change, which are different from those of the numerical control RDB of the 2169 stainless steel tube[6]. The maximum value of the cross section distortion degree decreases from 7.00% to 3.00% when the \( d \) increases from 5.0372mm to 5.4372mm. This is because that with increasing of the \( d \), the friction force between mandrel and inside wall of tube and the support role of the mandrel to the tube increase. Increasing the friction force makes the cross section distortion degree augment and increasing the support role of the mandrel to the tube leads to the cross section distortion degree decrease, while the support of the mandrel to the tube plays a leading role. Thus, the cross section distortion degree decreases with increasing of the \( d \). When the \( d \) is larger than 5.3872mm, continuing to increase the \( d \) has no obvious influence on the cross section distortion degree. The main reason is that the clearance between mandrel and tube is small at this moment (the value is 0.075mm), continuing to decrease the clearance is limited. Namely, increasing the \( d \) is limited. On the contrary, overlarge the \( d \) causes the tube to difficult to the bending deformation, which causes the outside wall of the tube over-thinning or even cracking, the front-end of the bent-tube wrinkling and the die acceleration wear[9]. When the \( d \) is less than 5.372mm, the maximum value of the cross section distortion degree is 5.08%, which has exceeded the upper limit of the requirement of the aviation standard of 5%. Thus, considering the influences of the \( d \) on the wall thinning and cross section distortion, the range of the optimal mandrel diameter is 5.2372mm-5.3872mm.

![Figure 5. Effect of \( d \) on wall thinning and cross section distortion: (a) wall thinning degree; (b) cross section distortion degree](image)

### 4. Conclusions

1. A 3D elasto-plastic FE model for the whole process of the TA18 high strength titanium alloy tube during numerical control RDB is developed based on FE software of ABAQUS, and its reliability is verified.
2. With the increase of the mandrel extension length \( e \) or mandrel diameter \( d \), the wall thinning augments, while the cross section distortion reduces.
3. The optimal range of the mandrel extension length \( e \) and mandrel diameter \( d \) is 0.5mm-1.5mm and 5.2372mm-5.3872mm, respectively.

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