Influences of mandrel types on forming quality of TA18 high strength tube in numerical control bending

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Abstract: In order to improve the forming quality and limit of tube numerical control (NC) bending, it is necessary to select reasonable mandrel types. A finite element (FE) model of the whole process of TA18 high strength tube in NC bending was established based on the platform of ABAQUS, and its reliability was validated. Then, using the model, the effects of no mandrel, cylindrical mandrel, hemispherical mandrel and ball-and-socket mandrel on the distribution of tangential stress/strain, wall thinning and cross section distortion were studied. The results show that the shape, size and location of the tangential stress/strain distribution have no obvious difference for the NC bending without mandrel and with three mandrel types. For the bending without mandrel, the wall thinning is the smallest, and the cross section distortion is the largest, which exceeds the requirement of aviation standard. Three types of mandrel have no significant effect on the wall thinning, while the hemispherical mandrel is the most conducive to control the cross section distortion.

1. Introduction

Due to excellently comprehensive performance such as low density, high strength-to-weight ratio, excellent corrosion resistance and high pressure resistance, the TA18 high strength tubes have attracted increasing applications in hydraulic tubing systems for advanced aircraft and engine [1]. Among various tube bending methods, the numerical control (NC) bending is the wide application, economical and precise method, and it can realize the precision and high efficiency bending forming for high strength titanium alloy tubes. Compared with stainless steel tubes and aluminum alloy tubes, the TA18 high strength tubes are more difficult to bending deformation. And the wall thinning or even cracking, serious cross section distortion of the TA18 high strength tubes are easy to generate after bending due to its characteristic of large yield ratio and low elongation. The mandrel plays an important role in tube bending process. The reasonable selection mandrel types can effectively restrain or reduce these defects, which can improve the forming quality and limit of tube bending. Therefore, to select the reasonable mandrel types, it is necessary to study the effects of mandrel types on forming quality of the TA18 high strength tube in NC bending. And according to the special requirement and application, the suitable mandrel shape is designed for tube bending.

Many scholars have carried out a lot of researches on the wall thinning and cross section distortion during tube bending process. But most of them focused on the effects of geometrical parameters, material parameters, process parameters and mandrel parameters on the wall thinning and cross...
section distortion. The study on the effects of mandrel types on the stress/strain, wall thinning and cross section distortion in tube bending are little involved. Veerappan and Shanmugam[2] derived the analytical formula of the cross section distortion for tube bending based on the assumptions of the linear, uniform and isotropic material model, steadily static loading conditions and no Bauchinger effects. Some theoretical formulae including stress, wall thickness variation, cross section distortion, curvature radius of neutral layer and bending moment based on the plane strain assumption and exponent hardening law were presented by Lu et al.[3]. Liu et al.[4,5] experimentally studied the effects of process parameters and various dies on the wall thickness distribution and cross section distortion of thin-walled rectangular 3A21 aluminum alloy tube NC bending. And the influence laws of the geometrical parameters and mandrel parameters on the wall thinning and cross section distortion were studied using the model. In recent years, for the annealing treatment TA18 titanium alloy tubes, the effects of geometry parameters, material parameters on forming quality of the high strength TA18 titanium alloy tubes in NC bending were numerically investigated by Fang et al.[8,9].

In order to select the suitable mandrel types and realize the precise bending, a 3D elastic plastic FE model of the whole process of the TA18 high strength tube with the specification of 6.35 mm × 0.4064 mm (diameter × wall thickness) in NC bending is established based on ABAQUS code, and its reliability is validated. Then, the effects of mandrel types on stress/strain distribution, wall thinning and cross section distortion of the TA18 high strength tube NC bending are investigated using the model, and the reasonable mandrel type is chosen. The results of the research may help to better understanding the mandrel role on improving the forming quality and limit of tube NC bending.

2. FE model and its reliability validation
According to the real tube NC bending process, a 3D elastic plastic FE model of the whole process of the TA18 high strength tube in NC bending was established based on the ABAQUS code as shown in Figure 1. The explicit algorithm was used for solving the bending tube and retracting mandrel operation, while the implicit one was employed for unloading process. The detailed modeling process and forming parameters can be seen in literature [8].

In order to validate the reliability of the FE model of the TA18 high strength tube in NC bending, simulation and analysis of the TA18 high strength tube with the specification of 9.525 mm × 0.508 mm in NC bending process were carried out based on the bending conditions in literature[10].

Figure 2 shows the comparison between FE simulation and experimental results gotten in Ref.[10] with respect to the wall thinning degree and cross section distortion degree. Here, the wall thinning degree is expressed as \( \Delta t = (t - t') / t \), where \( t \) is the initial wall thickness of the tube, \( t' \) is the wall thickness after bending deformation. The cross section distortion degree is written as \( \Delta D = (D - D') / D \), where \( D \) is the initial diameter of tube, \( D' \) is the vertical length of the cross section after bending. It is discovered that the FE simulation results of the wall thinning degree and cross section distortion degree agree with the experimental ones, and the relative error of the maximum value (error = \( |V_e - V_s| / V_s \times 100\% \)), where \( V_e \) and \( V_s \) denote experimental value and simulative value, respectively) of the wall thinning degree and cross section distortion degree is 13.6%, 13.8%, respectively. Thus, the results show that the FE model used in the study is reliable, which can be used to explore the forming quality of the TA18 high strength tube in NC bending under different mandrel types.
3. Results and discussion

During tube NC bending process, the reasonable selection mandrel types can effectively restrain or reduce forming defects, which can improve the forming quality and limit of tube bending. The mandrel types mainly include cylindrical mandrel, hemispherical mandrel and ball-and-socket mandrel in tube NC bending process as shown in Figure 3. Using the established 3D elastic plastic FE model, the influences of the mandrel types on stress/strain distribution, wall thinning and cross section distortion are simulated, and the reasonable mandrel type is chosen based on the simulation results.

3.1. Effects of mandrel types on stress and strain distribution

Figure 4 shows the tangential stress distribution of the TA18 high strength tube in NC bending under different mandrel types. It can be seen from Figure 4 that the maximum value of the tangential stress of outer side or inner side mainly distributes in the region near the bending plane. The reason is caused by the local progressive bending characteristics of tube NC bending, namely, the deformation occurs only in the local region near the bending tangent point [6]. The distribution of the tangential tensile stress in the vicinity of the bending plane is uniform and continuous for the bending without mandrel, while that of the bending with mandrel is discontinuous as shown in Figure 4(b), (c) and (d). The shape, size and position of the distribution of tangential compressive stress for the bending without mandrel are similar to those of the bending with mandrel. In the bending with mandrel, the shape, size and position of the distribution of the tangential tensile stress or compressive stress have no obvious difference under different mandrel types. It also can be seen from Figure 4 that the maximum value of the tangential compressive stress for the bending without mandrel and the bending with mandrel has little difference. This is because that the inner side of bent tube subjects to the constraint of the bending die cavity. The maximum value of the tangential tensile stress of the bending without mandrel
is larger than that of the bending with mandrel. The reason is that the inside of the bent tube has no mandrel support in the bending without mandrel, which makes the cross section distortion degree increase. Thus, the tangential tensile stress increases.

![Figure 4](image)

**Figure 4. Effects of mandrel types on the distribution of tangential stress (Pa)**

Figure 5 shows the tangential strain distribution of the TA18 high strength tube in NC bending with different mandrel types. It can be seen form Figure 5 that the tangential strain distribution of outer side or inner side is uniform and continuous for the bending without or with mandrel, and the shape, size and position of that are similar to each other. The tangential strain is large in the middle part and small in both ends. As can be seen from the magnitude of the tangential strain that the maximum value of the tangential tensile strain is the smallest and that of the tangential compressive strain is the largest for the bending without mandrel. This is because that there is no mandrel constraint in the bending without mandrel. The maximum value of the tangential strain has no obvious difference under different mandrel types for the bending with mandrel. The reason is that changing the partial structure of the mandrel has little influence on the maximum value of the tangential strain under the same mandrel parameters and process conditions.

![Figure 5](image)

**Figure 5. Effects of mandrel types on the distribution of tangential strain**

### 3.2. Effects of mandrel types on wall thinning and cross section distortion

Figure 6 shows the effects of mandrel types on wall thinning and cross section distortion of the TA18 high strength tube in NC bending. It can be seen from Figure 6(a) that the wall thinning degree of bent tube is small in the region near the bending plane and initial bending plane and large in middle part. 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 wall thinning degree is of a platform deforming characteristic with little change at the angle between 20° and 160°. Namely, the wall thinning degree has no obvious change. The wall thinning degree is the smallest for the bending without mandrel, and the maximum value of that is 5.92%. The maximum value of the wall thinning degree has little difference for the bending with cylindrical mandrel, hemispherical mandrel and ball-and-socket mandrel, and that is 8.15%, 8.34% and 8.18%, respectively. This is consistent with the maximum value of the tangential strain change little under different mandrel types as mentioned in
section 3.1. The main reason is that the friction force between the mandrel and the inner surface of the tube prevents the material of the straight-line segment behind the bending plane from flowing to the bending segment, which leads to the wall thinning degree increase. The larger friction force is, the larger the wall thinning degree is. The contact area between the mandrel and the tube from large to small are the hemispherical mandrel, ball-and-socket mandrel and cylindrical mandrel, and the larger the contact area is, the larger the friction force is under the same conditions.

Form Figure 6(b), It is found that the change law of the cross section distortion degree is similar to that of the wall thinning degree, namely, the cross section distortion degree is small in the bending plane and initial bending plane and large in the middle segment, and the platform deforming characteristic appears obviously in the middle part. The main reason is that the initial bending plane is clamped tightly by the clamp die and bending die, the bending plane is restrained by mold cavity or supported by mandrel and the middle segment is in a suspended state. The cross section distortion degree is the largest for the bending without mandrel, and the maximum value of that is 9.2%, which has exceeded the requirement of the aviation standard of 5%. This shows that the TA18 high strength tube during NC bending in the paper must add the mandrel to reduce the cross section distortion. The maximum value of the cross section distortion degree for the bending with cylindrical mandrel, hemispherical mandrel and ball-and-socket mandrel is 4.4%, 3.0% and 4.0%, respectively, which satisfies the requirement of aviation standard. This is because that, in the bending without mandrel, the cross section is easy to collapse because the tube lacks the support of mandrel, thus the cross section distortion degree is the largest. In the bending with mandrel, the cross section distortion of tube is small because of the support of the mandrel, and the value of the cross section distortion degree is relative to the support area of the mandrel. The larger the contact area is, the smaller the cross section distortion degree is. Therefore, taking the distribution of tangential stress/strain, wall thinning and cross section distortion of the TA18 high strength tube in NC bending under different mandrel types into consideration, the hemispherical mandrel is selected properly in this paper.

4. Conclusions
(1) The shape, size and location of the tangential stress/strain distribution have no obvious difference for the bending without mandrel or with three mandrel types.

(2) The wall thinning degree is the smallest and cross section distortion degree is the largest for the bending without mandrel. Three types of mandrel have no significant effect on wall thinning, while the hemispherical mandrel is the most conducive to control the cross section distortion.

(3) The optimal mandrel type is the hemispherical mandrel for the TA18 high strength tube NC bending.

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