Deformation Behavior of Medium-strength TA18 High-pressure Tubes During NC Bending with Different Bending Radii

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Abstract

To improve the forming quality and forming limit of the numerical control (NC) bending of high-pressure titanium alloy tubes, in this study, using three-dimensional (3D) finite element method, deformation behavior of medium-strength TA18 high-pressure tubes during NC bending with different bending radii is investigated. The results show that the cross-sectional deformation and the wall thickness variation during NC bending of TA18 tubes using a small bending radius (less than 2 times of tube outside diameter) are clearly different from that using a normal bending radius (between 2 and 4 times of tube outside diameter). For bending with a normal bending radius, with or without a mandrel, the distribution of the flattening in the bending area resembles a platform and an asymmetric parabola, respectively. For bending with a small bending radius, with or without a mandrel, the flattening both distributes like a parabola, but the former has a stable peak which deflects toward the initial bending section, and the latter has a more pronounced peak with a bending angle and deflects slightly toward the bending section. The wall thickness variations with a normal bending radius, with and without a mandrel, both resemble a platform when the bending angle exceeds a certain angle. For the bending with a small radius, the distribution of the wall thickness variation without a mandrel follows an approximate parabola which increases in value as the bending angle increases. If a mandrel is used, the thickening ratio increases from the initial bending section to the bending section.

Keywords: titanium alloy tubes; deformation behaviors; numerical control bending; finite element method; normal bending radius; small bending radius

1. Introduction

As a kind of key lightweight components, titanium alloy bent tubes have been increasingly used and have a promising future for finding a wider application in the aerospace, aviation and related high-technology industries, due to their advantages of high-pressure resistance, a high strength/weight ratio, long life, and so on \cite{1-3}. The rapid development has posed an urgent requirement for the exploitation of advanced plastic-forming technologies to bend high-quality tube parts. Among the various bending processes, the numerical control (NC) bending process, based on a rotary draw bending method, has become one of popular advanced technologies satisfying the above requirements, because of its many unique advantages, such as high efficiency, economy, process stability, and easier to actualize the digital precision forming and mass production \cite{4}.

However, in a NC bending process of medium-strength TA18 high-pressure tube, three-dimensional
(3D) compression stresses subjected to tube intrados will lead to wall thickness thickening, 3D tensile stresses subjected to tube extrados will lead to wall thickness thinning, and the resultant force of 3D compression and tensile stresses subjected to tube will lead to cross-sectional flattening. Especially, with a decrease of bending radii, the wall-thickness variation and the cross-sectional flattening will become larger. Furthermore, flattening of the cross-section and variation of the wall thickness are mutually dependent on each other, and they both have an important effect on the quality of the bent tubes. Thus, cross-sectional deformation and wall thickness variation are the main issues for NC bending of titanium alloy high-pressure tubes. In order to improve the bending limit and forming quality, further optimize and control the NC bending of titanium alloy tubes, and research and develop advanced NC bending technology, it is necessary to control the cross-sectional flattening and the wall-thickness variation of titanium alloy tubes during NC bending study, thus it is necessary to study deformation behavior in cross-sectional deformation and wall thickness variation of TA18 tubes during the process, especially with different bending radii.

Some work has been undertaken on the cross-sectional deformation and the wall thickness variation of tubes during bending using theoretical analysis, the finite element method (FEM) simulation and experimental research. Tang [5] has derived the expression for the change in wall thickness in the bending plane using plastic-deformation theory. Strano [6] has given the expression for the maximal flattening of the cross-section based on experimental data for steel tube bending. But, using the above expressions, it is difficult to find the characteristics in cross-sectional deformation and wall thickness variation of titanium alloy tubes in the whole bending area during NC bending with different bending radii.

Using the FEM and experimental method, Yang, et al. [7-17] have revealed the deformation behavior of wall thickness and cross-section of NC bending of stainless steel and aluminum alloy tubes under various bending conditions, including the action of the mandrel [7,9,16], the bending for the tube with large diameter and/or small bending radius [8,13], the action of the push assistant loading conditions [16], various process parameters [11,14-15,17,18], and various frictions between tube and dies [12].

In terms of bending titanium alloy tubes, only Hur and Park [18] have achieved 360° multistep cold bending with a larger bending radius for a Ti-6Al-4V seamless tube. And Jiang, et al. [19,20] have established a 3D FE model for the NC bending of medium-strength TA18 titanium alloy tubes and analyzed the coupling effects of the bending angle and the material properties on the springback behavior.

So far, much research about the deformation behaviors has focused on the bending of aluminum alloy and stainless steel tubes. Considering that titanium alloy tubes have some special properties different from aluminum alloy or steel tubes, such as apparent anisotropy, high yielding and tensile strength, and low elongation at room temperance, the coupling of unique material properties of titanium tubes and severe quality request for high-pressure tubes makes the deformation behavior of titanium alloy tubes during NC bending with different bending radii different from those of stainless and aluminum alloy thin-walled tubes to some degree. Therefore, the aim of the present work is to investigate the deformation behavior, including the cross-sectional deformation and the wall-thickness variation of medium-strength TA18 titanium alloy tubes during the NC bending with different bending radii.

2. Materials and Method

2.1. Tube specifications and material properties

The medium-strength TA18 titanium alloy tubes which have been used as high-pressure hydraulic tubing in aviation field have an outer diameter of about 6-25 mm and a wall thickness of 0.6-2.5 mm. The appropriate die sets for TA18 tubes with a diameter of less than 12 mm require a bending die, a clamp die and a pressure die. If the diameter is at least 12 mm, then a mandrel should also be included. Two typical tubes are chosen: 8 mm × 0.8 mm, and 14 mm × 1.35 mm (denoted D × t, where D and t are the outside diameter and wall thickness of a tube, respectively). They are manufactured by Northwest Institute for Non-ferrous Metal Research in China. Their material properties, obtained by uniaxial tensile testing, are presented in Table 1, where the Hollomon model \((\sigma = K e^n\), where \(\sigma\) is flow stress, \(e\) the strain) is used to describe their strain hardening behavior, as it closely approximates to their true stress-strain curve.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus E/GPa</td>
<td>94.412</td>
</tr>
<tr>
<td>Extensibility ε (%)</td>
<td>19.978</td>
</tr>
<tr>
<td>Initial yield stress σy/MPa</td>
<td>569.582</td>
</tr>
<tr>
<td>Ultimate tension stress σu/MPa</td>
<td>648.229</td>
</tr>
<tr>
<td>Strength coefficient K/MPa</td>
<td>931.0</td>
</tr>
<tr>
<td>Hardening exponent n</td>
<td>0.011</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 mm×0.8 mm</td>
<td>100.177</td>
</tr>
<tr>
<td>14 mm×1.35 mm</td>
<td>21.698</td>
</tr>
<tr>
<td>560.609</td>
<td></td>
</tr>
<tr>
<td>725.136</td>
<td></td>
</tr>
<tr>
<td>978.9</td>
<td></td>
</tr>
<tr>
<td>0.085</td>
<td></td>
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</tbody>
</table>

2.2. FE model and computational condition

The explicit elastic-plastic 3D FE models for the NC bending of TA18 tubes of various specifications were quickly established using a pre-processing module developed by H. B. Jiang, et al. [21] and the key technologies discussed by Z. Q. Jiang, et al. [19]. Fig. 1 shows an FE model which includes a bending die, a clamp die, a pressure die, and a mandrel. If the diame-
ter of the tube is below 12 mm, then the effects of the mandrel during bending can be ignored by suppressing them in the model.

During the simulation, tubes were assumed to be homogeneous and isotropic, to follow the von Mises yield criterion, and to experience negligible strain rate and temperature effects. The friction coefficients between the tube and dies were obtained using an MMX-2 friction and abrasion testing machine (see Table 2).

Table 2  Friction conditions in various interfaces

<table>
<thead>
<tr>
<th>Contact interface</th>
<th>Friction coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube outside surface—pressure die</td>
<td>0.25</td>
</tr>
<tr>
<td>Tube outside surface—bending die</td>
<td>0.10</td>
</tr>
<tr>
<td>Tube inside surface—mandrel</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Considering the ability to deform plastically, the strength of TA18 tubes at room temperature and the aerial requirements, the normal bending radius is defined as 2-4 times of the outside diameter of the tube. And the bending radius is defined as less than 2 times of the outside diameter of the tube.

### 2.3. Forming index

A few indices are used to measure the variation in wall thickness and cross-section of NC bending of TA18 titanium alloy tubes. The change ratio in the wall thickness is expressed as

\[ I_t = \frac{t' - t}{t} \times 100\% \]  

where \( t \) is the initial wall thickness of the tube, \( t' \) the wall thickness after bending, and the positive and negative values of it indicate thickening and thinning of the wall, respectively. Since the variations in the outside and inside crest lines (see Fig. 2) are the largest, only the wall change ratios along the two crest lines are given in the following analysis. Because of the special restrictions in NC bending, the cross-sectional deformation is mainly induced by the vertical reduction of the tube cross-section. Thus, the cross-sectional flattening can be written as

\[ I_d = \frac{D - D'}{D} \times 100\% \]  

where \( D \) is the initial outside diameter of the tube, and \( D' \) the vertical length of the cross-section after bending. A larger value of \( I_d \) indicates more severe deformation of the cross-section. In order to measure the wall-thickness variation and the cross-sectional deformation during NC bending, some measuring planes through the bending center \( O \) are defined in the bending area. A typical measuring plane is plane \( A-A \) (see Fig. 2), in which \( \theta \) is the bending angle, and \( \alpha \) the angle between the measuring plane and the initial bending section. Obviously, at a given bending angle, a smaller value of \( \alpha \) means that the measurement is nearer to the initial bending section. A larger angle of \( \alpha \) means that the measuring plane is nearer to the bending section.

### 2.4. Model verification

The reliability of the FE models for the NC bending of 8 mm × 0.8 mm tubes has been testified in Ref. [19]. And using the FE models and the bender, the simulation and experimental verification for the NC bending of 14 mm × 1.35 mm TA18 tubes are carried out, in which the bending radius \( R \) is 35 mm. The wall thickness of the bent tubes is measured using a micrometer screw gauge, and the cross-sectional deformation of bent tubes is measured using a square caliper. Fig. 3 shows the configuration of some bent 14 mm × 1.35 mm × 35 mm (denoted \( D \times t \times R \), where \( D \), \( t \) and \( R \) are the outside diameter, wall thickness and bending radius of a tube, respectively) TA18 tubes. Observation and measurement of the surfaces of these bent tubes show that there is no wrinkling, fracture, or surface defects (such as fish tails, indentations, or hips). Table 3 shows the maximum values of wall thinning, wall thickening, and the cross-sectional flattening obtained from FEM simulation and experiment. As can be seen from Table 3, the value of the thickening ratio...
is larger than that of the thinning ratio, which accords with the results using analytic models [5]. The maximum relative error in the simulation and experimental results is less than 15%. All these results show that the FE models used in our study are acceptable. The error may be resulting from that the wall thickness and length of axes during the experiment are difficult to measure accurately.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Wall thinning, wall thickening and flattening of cross-section from FEM simulation and experiment</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>FEM</td>
</tr>
<tr>
<td></td>
<td>Simulation</td>
</tr>
<tr>
<td></td>
<td>Experiment</td>
</tr>
<tr>
<td>Relative error</td>
<td>13.75</td>
</tr>
</tbody>
</table>

3. Results and Discussion

3.1. Deformation behavior of cross-section

Fig. 4 shows the cross-sectional flattening at various bending angles for the NC bending of 8 mm×0.8 mm and 14 mm×1.35 mm tubes with normal bending radii. In Fig. 4, the normal bending radii for 8 mm×0.8 mm and 14 mm×1.35 mm TA18 tubes are 24 mm and 35 mm, respectively. From Fig. 4, it can be seen that the deformation behavior of the cross-section for the bending of 14 mm×1.35 mm×35 mm TA18 tubes obviously differs from that for the 8 mm×0.8 mm×24 mm tubes.

As can be seen from Fig. 4(a), when the bending angle is less than a critical value (here about 30°), the distribution of the cross-sectional flattening from the initial bending section to the bending section is like a parabola. The larger the bending angle, the larger the cross-sectional flattening in the middle of the area of deformation. But when the bending angle reaches the critical value, the distribution of the cross-sectional flattening from the initial bending section to the bending section is like a plateau, and the flattening in the middle of bending section changes slightly, but only the length increases as the bending angle increases, which means that the cross-sectional flattening almost reaches a steady state at this critical bending angle. This characteristic is different from that of the NC bending for 1Cr18Ni9Ti stainless steel and LF2M alloy thin-walled tubes with R=2D [14]. In Ref. [14], the cross-sectional flattening always increased with the bending angle and it varied along the bending area like an asymmetric parabola with a peak deflecting slightly toward the initial bending section. This is due to the fact that a TA18 tube with an outside diameter below 12 mm does not have a mandrel in it during the bending process, thus the cross-sectional flattening occurs mainly when the cross-section is near the bending section. Once the cross-section has passed the deformation region, the bent segment of the tube only deforms slightly due to the hardening of the material, thus the shape of the cross-section barely changes any more.

As can be seen from Fig. 4(b), the distribution of the cross-sectional flattening for the bending of 14 mm×1.35 mm×35 mm is like an asymmetric parabola and the maximum of the cross-sectional flattening increases a little as the bending angle increases, which is similar to that of the NC bending for 1Cr18Ni9Ti stainless steel and LF2M alloy thin-walled tubes [14]. And the peak of TA18 tubes deflects slightly toward the bending section at a larger bending angle, which is different from that of the NC bending for 1Cr18Ni9Ti stainless steel and LF2M alloy thin-walled tubes [14]. In Ref. [14], the peak of the cross-sectional flattening deflects toward the initial bending section due to the absence of mandrel and balls in the area and the lower anti-flattening ability of thin-walled tubes. But for a TA18 tube with an outside diameter at less than 12 mm, a mandrel acts to slightly flatten the cross-section near the bending section, and the cross-section a little far away from the bending section flattens considerably without support from the mandrel. As the bending proceeds, the bending angle increases, the deformed area also increases, and the high strain hardening effect of the deformed area makes the cross-section in the area flatten a little and the peak deflect slightly toward the bending section.

Fig. 5 shows the cross-sectional flattening at various bending angles for the NC bending of 8 mm×0.8 mm and 14 mm×1.35 mm tubes with small bending radii, respectively, in which, the small bending radii for 8 mm×0.8 mm and 14 mm×1.35 mm tubes are 8 mm
and 21 mm, respectively. From Fig. 5, it can be seen that the deformation behavior of the cross-section for the bending of 14 mm×1.35 mm×21 mm and 8 mm×0.8 mm×8 mm TA18 tubes is also obviously different from each other. Also, the distributions of the cross-sectional flattening and the variation with the bending angle for the 8 mm×0.8 mm and 14 mm×1.35 mm tubes with a small bending radius differ from those with the normal bending radius (see Fig. 4).

Fig. 5 Variation of cross-section with bending angle (small bending radii).

Fig. 5(a) shows that the distributions of the cross-sectional flattening for an 8 mm×0.8 mm tube with a bending radius of 8 mm are parabolic and the value of the flattening obviously increases with the bending angle, which is similar to that of the NC bending for 1Cr18Ni9Ti stainless steel and LF2M alloy thin-walled tubes with \( R \leq 1.5D \) \([9,15-16]\). But the peak of the parabola deflects slightly toward the bending section, which is different from that of the NC bending for 1Cr18Ni9Ti stainless steel and LF2M alloy thin-walled tubes \([9,16]\). In Ref. [9] and Ref. [16], the peak of the cross-sectional flattening deflected slightly toward the initial bending section. This occurs because the outside wall of the tube near the bending section collapsed inward for the 8 mm×0.8 mm TA18 tubes with a small bending radius without a mandrel in the tube (see Fig. 6). The larger the bending angle, the more obvious is the inward collapse (see Fig. 7). The larger amount of inward collapse also reduces the anti-flattening ability of the cross-section. These effects substantially increase the cross-sectional flattening as the bending angle increases.

Fig. 6 Inward collapse of outside wall.

Fig. 7 Variation of inward collapse of outside wall with bending angle for 8 mm×0.8 mm×8 mm tubes.

As can be seen in Fig. 5(b), the distribution of the cross-sectional flattening for the 14 mm×1.35 mm tube with a bending radius of 21 mm also resembles an asymmetric parabola, but the peak deflects toward the initial bending section, which is similar to that of the NC bending for 1Cr18Ni9Ti stainless steel and LF2M alloy thin-walled tubes \([9,15-16]\). And the maximum flattening of the cross-section increases as the bending angle increases when the angle is less than a critical value (about 40°), but when the bending angle is larger than the critical angle, the maximum flattening of the cross-section and its position change slightly. This is because that when the bending angle is small, the cross-section just beyond the bending section flattens, which mainly results from the lack of support from the mandrel. As the bending angle increases, the outside wall collapses inwardly in an uniform manner and there is an increasing mismatch with the bending die from the bending section to the initial bending section, which means that the most severe flattening is always located in the zone near the initial bending section when a small bending radius is used (see Fig. 8).

3.2. Deformation behavior of wall thickness

Figs. 9-10 show wall-thickness variations along the outside and inside crest lines during NC bending for
Fig. 8  Inward collapse of outside wall and mismatch of inside wall for 14 mm×1.35 mm×21 mm tubes.

Fig. 9  Variation of wall thickness with bending angle (normal bending radii).

Fig. 10  Variation of wall thickness with bending angle (small bending radii).

As can be seen from Fig. 9, the deformation behavior of the wall thickness for the bending of 14 mm×1.35 mm×35 mm and 8 mm×0.8 mm×24 mm TA18 tubes are similar to each other. When the bending angle is below a certain value (here about 40°) the wall-thickness changing ratio firstly increases and then decreases from the initial bending section to the bending section for NC bending of 8 mm×0.8 mm and 14 mm×1.35 mm tubes with the normal bending radius, and the wall-thickness variation in the midst of the bending deformation area increases gradually as the bending angle increases. When the bending angle exceeds the critical angle, the wall-thickness change ratio first increases, then hardly changes and finally decreases along the crest lines from the initial bending section to the bending section, and the maximum value of the wall change ratio varies slightly as the bending angle increases.

In other words, when the bending angle reaches the critical value, the wall-thickness variation is of a platform deforming characteristic with little change near the clamp die and pressure die, and with the increase of the bending angle, the value of wall change ratio in the platform zone changes slightly and only the length of platform increases, which differ from those of the NC bending for LF2M alloy thin-walled tubes with $R=2D$ [17]. In Ref. [17], the thinning of LF2M tubes increases with the bending angle, and it does not always distribute like a parabolic along the outside crest line under various conditions. This is due to that, a TA18 tube will gradually reach a steady deformation stage as the bending process proceeds when the bending angle is below the critical angle until the contact, friction, and interaction between the tube and dies reach the stable state when the bending angle reaches the critical value.

As can be seen from Fig. 10(a), for the bending of 8 mm×0.8 mm TA18 tubes with the small bending radius, the distribution of the wall-thickness change
ratio along the crest lines resembles a parabola, the value of the wall-thickness change ratio always increases with the increase of the bending angle, and the increase of the wall thickening ratio is larger than that of the thinning ratio. These are similar to those for the NC bending for 1Cr18Ni9Ti and LF2M alloy thin-walled tubes at some degree [8]. In Ref. [8], the wall thinning and thickening increased greatly with the bending angle, and at latter bending stages, i.e., the bending angle reached a larger value, the thinning and thickening varied little. That phenomenon was explained by the local progressive deformation of thin-walled tube NC bending by Li, et al [8]. But the wall-thickness variation of 8 mm×0.8 mm TA18 tubes with small bending radius differs from that with the normal bending radius (see Fig. 9(a)). This is because the outside wall collapsed inward largely during the bending of an 8 mm×0.8 mm TA18 tube with a small bending radius (see Fig. 6), which makes the true bending radius for the outside wall less than the given value.

As can be seen from Fig. 10(b), for the bending of 14 mm×1.35 mm TA18 tubes with a small bending radius, the distribution of the wall thickness thickening ratio along the inside crest line increases from the initial bending section to the bending section, which is different from that with the normal bending radius (see Fig. 9(b)) and similar to that form the NC bending for 1Cr18Ni9Ti and LF2M alloy thin-walled tubes at some degree [8]. But the distribution of the wall thinning ratio along the outside crest line is still platform-like, which is similar to that with the normal bending radius (see Fig. 9(b)). This is because a mandrel is used for the bending of the 14 mm×1.35 mm×21 mm TA18 tubes, thus the outside wall cannot collapse so much, so the thinning ratio of the outside wall retains a platform-like shape. But as the bending angle increases, the strain hardening of the deformed area makes more and more material accumulate in the area near the bending section, which leads to an increase in the thickening ratio near the bending section with the bending angle.

3.3. Experimental

From the results of Section 3.1 and Section 3.2, it can be concluded that, the deformation behavior of wall thickness and cross-section during NC bending of medium-strength TA18 high-pressure tubes with a small bending radius and with a normal bending radius are clearly different from each other, and they are also different from those from NC bending of 1Cr18Ni9Ti and LF2M alloy thin-walled tubes.

(1) The deformation behavior of wall thickness and cross-section during NC bending of medium-strength TA18 high-pressure tubes with a small bending radius and with a normal bending radius are clearly different from each other, and they are also different from those from NC bending of 1Cr18Ni9Ti and LF2M alloy thin-walled tubes.

(2) For bending with a normal bending radius, the distribution of the flattening in the bending area looks like a plateau if a mandrel is not being used. If a mandrel is applied, then the distribution resembles an asymmetric parabola with the peak located in the area where the mandrel no longer offers support.

(3) If the bending radius is small and a mandrel is not being used, the flattening distributes like a parabola with a peak deflecting toward the bending section due to the increasing inward collapse of the outside
wall near the bending section, and it increases as the bending angle increases. If a mandrel is used, the flattening also resembles an asymmetric parabola but with a stable peak deflecting towards the initial bending section, due to the almost uniform collapse of the outside wall and an increasing mismatch from the bending section to the initial bending section.

(4) The wall-thickness variations along the crest lines with or without a mandrel and with a normal bending radius are similar. They both resemble a plateau when the bending angle exceeds the critical angle.

(5) If the bending radius is small, the distribution of the wall-thickness changing ratio without a mandrel resembles a parabola with the value increasing with the bending angle. The thinning ratio when a mandrel is used distributes similarly to that with a normal bending radius but the thickening ratio distributes differently, and it increases from the initial bending section to the bending section.

References


Biographies:

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