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ARTICLE

Section Flattening in Numerical Control Bending Process of TA18 High Strength Tube

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Abstract: Section flattening is an inevitable physical phenomenon in the forming process of tube bending, and severe section flattening will affect the reasonable assembly of the tube fittings, and therefore restricts its wide application. Finite element (FE) model for numerical control (NC) bending of titanium tube considering the variation law of contractile strain ratio (CSR) and the Young's modulus (*E*) was established in the present paper. The section flattening behaviors of TA18 tube under different geometric conditions and different process conditions were investigated. The results show that considering the variation law of CSR-*E* can change the cross-section, which has no remarkable influence on the change law. The reasonable range of geometric and process parameters are obtained, which provides a basis for studying the forming prediction and controlling the final precision for the NC bending of TA18 tube.

Key words: titanium alloy tube; NC bending; section flattening; contractile strain ratio; Young's modulus

Titanium alloy tube has desirable combination of characteristics such as low Young's modulus (*E*), high strength, clear anisotropy (the anisotropy of tube is usually described in terms of the contractile strain ratio (CSR))[1,2]. CSR and *E* are important parameters that affect the plastic forming quality of titanium alloy tube[3]. Also, the section flattening of a qualified bending tube should meet the aviation standards. Unfortunately, if the forming precision of the section flattening is not predicted precisely, it will limit the improvement in the quality of titanium alloy tube bending parts. Accurate and effective prediction and control of titanium alloy tube numerical control (NC) bending can finally achieve precise forming, and that must be on the basis of the cross-section flattening to meet the aviation standards and it requires a reasonable bending parameters of the titanium alloy tube. Therefore, it is urgent to research the section flattening law of titanium alloy tube bending under different conditions.

In recent years, many scholars have carried out the research of section flattening of tube bending. Based on the plane stress assumption and combined with the maximum shear stress yield criterion and the material flow theory, the theoretical prediction formula of the section flattening condition of the tube during bending process was established. However, due to the simplification and assumptions in the derivation process, its accuracy and practicality were limited[4]. By means of analytical methods, an approximate displacement field for the cross-section of the tube during the bending process was established. The strain of the tube was described by the dis placement field, and the section flattening characteristics in the tube bending process were studied based on the whole theory and the minimum energy principle. Nevertheless, the simplification and assumption were used in this study, such the accuracy of the results to be improved[5]. Stachowicz[6] analyzed the cross-section deformation behavior of the brass

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tube during bending under axial assisting force using the plasticity theory. He found that the shape of the cross-section after bending was different from ellipse, and the deformation of the outer tensile zone was more obvious than that of the inner compression region, especially the effect of axial assisting force was particularly pronounced when stress was shifted and asymmetrical. But this method is only applicable to the process of the intermediate frequency induction heating tube and the bending process. The method is not suitable for the NC bending process with multi-die constraints.

We know that the finite element (FE) method has already proved to analyze the tube bending and prediction of defect that may occur. Lee et al.[7] used an explicit FE model to simulate the flattened deformation characteristics of the elliptical tube during bending process, and obtained the elliptical tube forming limit based on the section flattening. In Ref. [8,9], the aluminum alloy rectangular tube bending model was established. Through the FE simulation, the section flattening behavior of tube bending under different loading paths and friction parameters was studied. Yang et al.[10] used the PAM-STAMP software to simulate the NC bending process of seamless steel tube which was used in the manufacture of automotive connecting rod parts by 3D elastic-plastic FE method. The section flattening behavior of tube was studied. Dyment et al.[11] have shown that the push assistant helped the tube to enter the bend-deformed zone and made the bending neutral layer move outside. As the push assistant level increased, the strain on the outside of the tube decreased, while the wall thickness increased. In Ref. [12-14], the deformation behaviors of stainless steel and aluminum alloy under different process conditions and geometric conditions were systematically studied by means of experimental and FE methods. The results showed that the bending angle was an important factor affecting the section flattening. The bending angle increased and the ellipticity rate increased. The hoop strain in the bending radius of the small bending radius should not be neglected. The section flattening defects more easily appeared in aluminum alloy tube than in the stainless steel tube. Pushing could improve the bending quality of tube parts.

However, in the above FE model, the CSR and E are assumed to be constants that do not vary with strain. In this kind of method, especially for TA18 high strength tube with significant anisotropy and low E, the simulation results show a large deviation from the experimental results to a certain extent. Zhang[15] established the 3D elastic-plastic FE model of TA18 high strength tube considering the variation of E. In her research, only the E characteristics with strain change were considered, and the CSR and its variation law of TA18 high strength tube with clear anisotropy were neglected, which would affect the prediction accuracy to a certain extent. Poursina et al.[16] found that in the case of CSR＜1, the larger CSR value could lead to a larger section flattening. The study also only considered the impact of CSR. That is, the above mentioned literature did not consider the variation law of CSR-E during tube bending. However, the actual CSR and E of the tube were changed with the plastic deformation increasing.

In the present study, a FE model of TA18 high strength tube NC bending process considering the variation law of CSR-E was established. The variation law of section flattening under different geometric conditions and process conditions was investigated. The reasonable parameters of section flattening of the tube NC bending to meet the aviation standard were obtained, and it provided the basis for the selection of reasonable geometric and process parameters to achieve final precise forming of TA18 high strength tube.

1 FE Modeling

In the present study, the size of TA18 high strength tube included tube outside diameter 12 mm and wall thickness 0.9 mm. In order to simulate the section flattening variation law of TA18 high strength tube, based on the FE software ABAQUS platform, a user material subroutine VUMAT which considers the variation of CSR-E with plastic deformation, was developed based on the Hill's1948 anisotropic yielding function and embedded into the FE model for the NC bending process of TA18 high strength tube. The values of CSR-E are shown in Eq. (1) and Table 1.

$$\begin{cases} \mathrm{CSR} = C_0 + f_1(C_s - C_0)[(1-\exp(-g_1\varepsilon_a^p))] + f_2(C_s - C_0)[(1-\exp(-g_2\varepsilon_a^p))] \\ E_u = E_0 - (E_0 - E_a)[1-\exp(-\xi\varepsilon_a^p)] \end{cases} \quad (1)$$

where, C_0, C_s are the initial value and the steady value of CSR, respectively; f_1, f_2 are the first-order decay component and the second-order decay component, respectively; g_1, g_2 are the first-order decay coefficient and the second-order decay coefficient, respectively; ε_a^p is the axial strain; E_u, E_0, E_a are the varied values, the initial value and the steady value of Young's modulus, respectively. In the modeling, the 1/2 model was used to improve the calculation efficiency because the tube was symmetrical. At the same time, the mandrel support was adopted in the model. According to the characteristics of TA18 high strength tube NC bending process, the precision and efficiency of FE simulation of TA18 high strength tube NC bending and unloading spring-back were studied. According to the practical tube bending process, a 3D FE model of the NC bending process was established based on the ABAQUS/ Explicit and the unloading spring-back process was established based on the ABAQUS/implicit, as shown in Fig.1. The main parameters of the FE model under different conditions are shown in Table 2.

Table 1 Parameters of physical equation of CSR- ε_a^p and E- ε_a^p for TA18 high strength tube

Parameter	C_0	C_S	f_1	f_2	g_1	g_2	E_0	E_a	ξ
Value	5.40295	1.11687	0.76038	0.23962	244.4988	35.72704	100.38	94.11	59.08

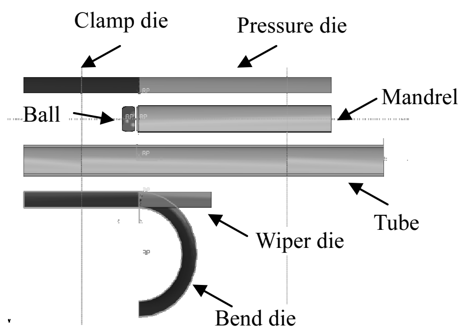

Fig.1 FE model for the NC bending of TA18 high strength tube

Modeling reliability validation: In order to verify the reliability of the above proposed model of NC bending, the experiment of TA18 high strength tube has been carried out on a W27YPC-63 NC bending machine. The reliability of the FE model was verified by the wall thinning, the section flattening and the spring-back angle of the tube after bending. In comparison, the same bending parameters were used in FE simulations and experiments. In order to quantitatively verify the reliability of the model, the reduction degree of the wall thickness, the flattening degree of the cross-section and the spring-back angle obtained from simulation and experiment for TA18 high strength tube bend angle at 90° were compared, as shown in Fig.2. From Fig.2, the predictions of FE model obtained by considering the variation law of CSR-*E* changes are in good agreement with the experimental results. Therefore, the FE model of TA18 high strength tube NC bending is reliable.

2 Results and Discussion

2.1 Section flattening distribution under different geometric conditions

Fig.3 shows the section flattening of TA18 high strength tube at different *R*/*D* predicted by FE analysis with and without considering the variation law of CSR-*E*. It can be found that the section flattening law is similar whether the two parameter variation laws are considered or not. The section flattening degree of considering the CSR-*E* variation is greater than that of ignoring it. Under the two conditions, the flattening degree of the cross-section decreases with the increase of *R*/*D* value. The maximum value of the sectional flattening degree has exceeded the maximum limit of 5% (aviation standard) when *R*/*D*=1. The tube has a serious flattening and may have been fractured. The flattening degree of the cross-section at the cross section of 10° from the starting section of the bending reaches the maximum, and then shows a decreasing trend when *R*/*D*=2 and *R*/*D*=3.

Fig.4 shows the section flattening of TA18 high strength tube at different bending angles predicted by FE analysis with and without considering the variation law of CSR-*E*. It can be found that the section flattening law is similar whether the two parameters variation laws are considered or not. The section flattening degree of considering parameters variation laws is greater than that of without considering them. After the bending angle is greater than 10° from the starting section, the flattening degree of the cross-section will reach a stable slow down stage. The flattening rates of the cross-sections at each bending angle are within the range of the aviation standard.

Table 2 Bending parameters under different geometric conditions and different process conditions

Parameter	Value					
Relative bending radius, *R*/*D*	1	1.5	2	3	-	-
Bending angle/(°)	30	60	90	120	150	180
Mandrel extension, *e*/mm	0	1	2	3	-	-
Pressure coefficient of pressure mold and tube, u_p	0.2	0.25	0.3	-	-	-
Friction coefficient of bending die and tube, u_b	0.05	0.1	0.15	-	-	-
Push assistant speed level, f_p/%	80	90	100	110	120	-

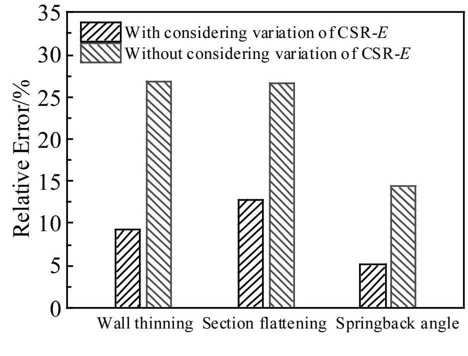

Fig.2 Comparison of results between FE simulations and experiments for TA18 high strength tube

2.2 Distribution of cross section under different process conditions

Fig.5 is the section flattening of TA18 high strength tube at different mandrel extension lengths predicted by FE analysis with and without considering the variation law of CSR-*E*. The distribution law of section flattening is similar whether the two parameters variation laws are considered or not. The section flattening degree of considering the parameters variation is greater than that of without considering them. The section flattening decreases gradually with the increase of mandrel extension lengths, and then increases slightly when the amount of extension increases to a certain value. This is

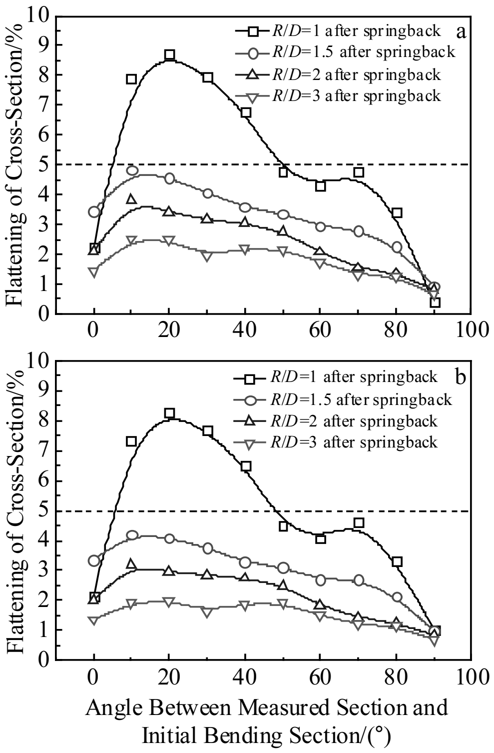

Fig.3 Section flattening of TA18 high strength tube at different *R*/*D*: (a) considering the variation law of CSR-*E* and (b) without considering the variation law of CSR-*E*

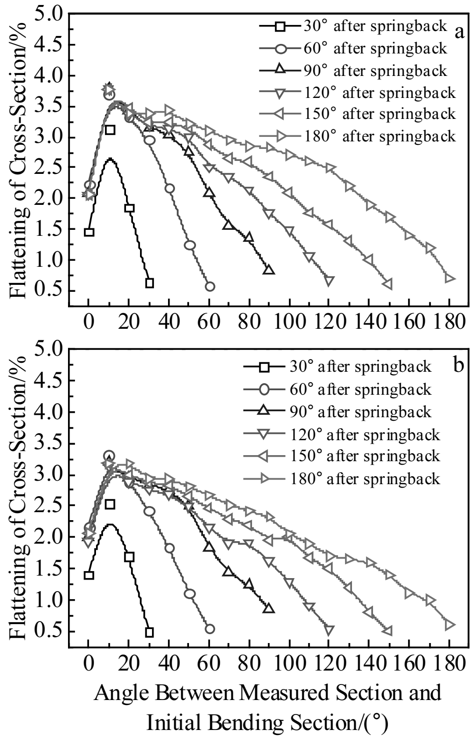

Fig.4 Section flattening of TA18 high strength tube at different bending angles: (a) considering the variation law of CSR-*E* and (b) without considering the variation law of CSR-*E*

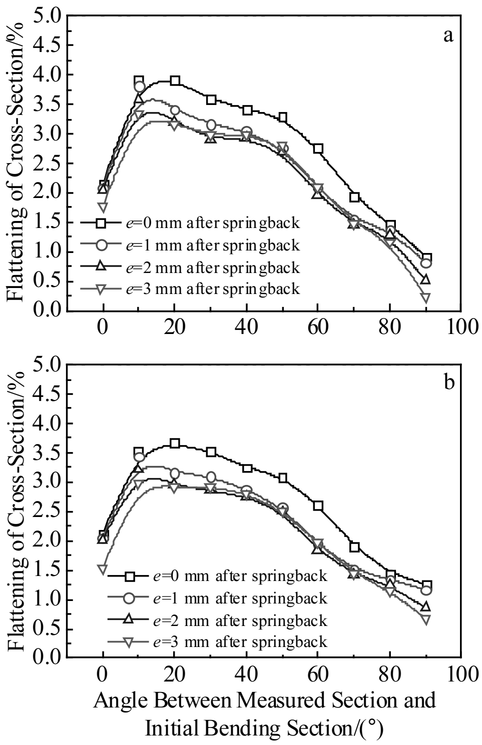

Fig.5 Section flattening of TA18 high strength tube at different mandrel extension lengths: (a) considering the variation law of CSR-*E* and (b) without considering the variation law of CSR-*E*

mainly due to the fact that the mandrel plays a supporting role during tube bending. The tangency point of mandrel hinders the smooth flow of material, resulting in the increase of wall thinning degree and the section flattening degree when the mandrel extension lengths increase to a certain value.

Fig.6 reveals the section flattening of TA18 high strength tube at different friction coefficients between pressure die-tube predicted by FE analysis with and without considering CSR-*E* variation. The distribution law of section flattening is similar whether the two parameters variation laws are considered or not. The section flattening degree of considering the two parameters variation is greater than that of without considering them. The section flattening decreases gradually with the increase of friction coefficients, but the degree of change is not significant. This is mainly due to the large friction between pressure die-tube playing the role of the pressure die side of the push. The material is more effectively pushed into the bending deformation region to reduce the tangential tensile stress outside the tube; therefore the section flattening shows a decreasing trend, and the maximum value is less than 5% of the aviation standard.

Section flattening of TA18 high strength tube at different friction coefficients between bending die-tube with and without considering the variation of CSR-*E* are shown in Fig.7.

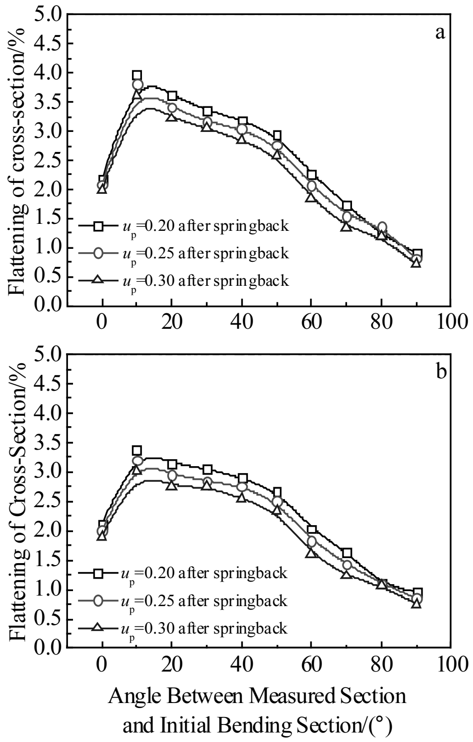

Fig.6 Section flattening of TA18 high strength tube at different friction coefficients between pressure die-tube: (a) considering the variation law of CSR-*E* and (b) without considering the variation law of CSR-*E*

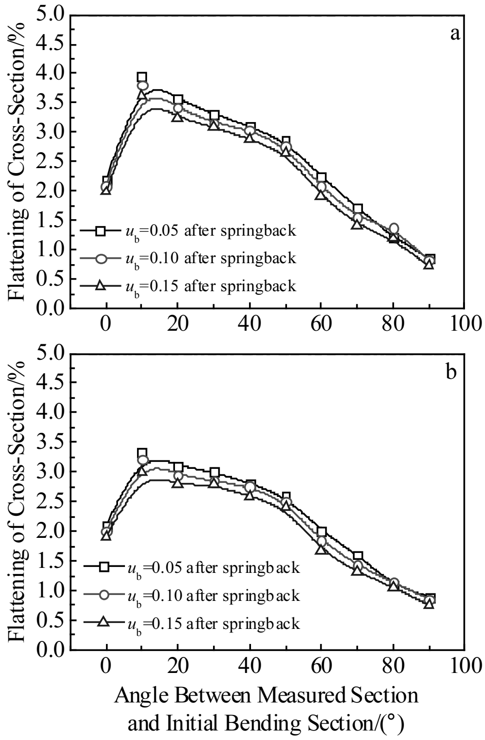

Fig.7 Section flattening of TA18 high strength tube at different friction coefficients between bending die-tube: (a) considering the variation law of CSR-*E* and (b) without considering the variation law of CSR-*E*

It can be found that the distribution law of section flattening is similar whether the two parameters variation laws are considered or not. The section flattening degree of considering the parameters variation is greater than that of without. With the increase of the bending dies and the friction coefficients, the degree of section flattening near the bending plane of the TA18 high strength tube NC bending slightly decreases. This is mainly due to that the large frictional resistance reduces the bending tangential compressive stress.

Fig.8 shows the section flattening of TA18 high strength tube at different relative push assistant speeds predicted by FE analysis with and without considering CSR-*E* variation. The distribution law of section flattening is similar whether the two parameters variation laws are considered or not. However, the section flattening degree of considering the parameters variation is greater than that of ignoring them. When the push assistant speeds level is less than 100%, the section flattening rate is larger. When the push assistant speeds level is greater than or equal to 100%, the flattening rate of the section is obviously smaller than the former. The difference of sectional flattening rate is not significant in above three cases. This is maybe due to the fact that the pressure die speed is less than the bending speed when the push assistant speeds level is less than 100%. It means that the axial friction force applied to the outside of the pressure die is opposite to the bending direction,

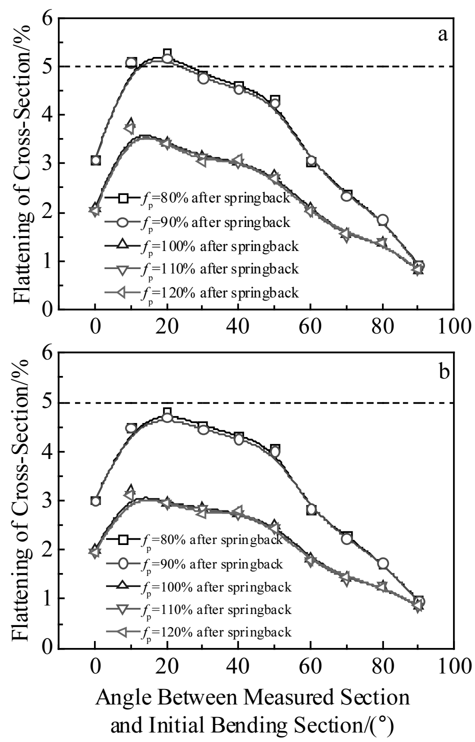

Fig.8 Section flattening of TA18 high strength tube at different relative push assistant speeds: (a) considering the variation law of CSR-*E* and (b) without considering the variation law of CSR-*E*

which increases the tensile stress at the outside of the tube, resulting in the increase of section flattening degree.

Under the condition of the push assistant level less than 100%, the maximum rate of section flattening of TA18 high strength tube has exceeded the aviation standard when ignoring CSR-*E* variation. That is, the obtained push assistant level is safer when considering the two parameters variation law.

3 Conclusions

1) FE model for NC bending of Φ12 mm×t0.9 mm TA18 high strength tube considering the variation law of CSR-*E* is established. The section fattening law under different geometric conditions and different process conditions is studied.

2) The cross section distribution law of tube NC bending under different geometric conditions and process conditions is expounded. The variation law of CSR-*E* will make the value of section flattening larger, but has no significant influence on the law of change.

3) The reasonable range of parameters are as follows: bending radius range is not less than 1.5 times of the outer diameter; bending angle is up to 180°; mandrel extension degree is 0~3 mm; friction coefficient between pressure die-tube and that between bending die-tube have no significant effect on the section flattening of tube NC bending. So the friction coefficient between pressure die-tube is in the range of 0.20~0.35, and that between bending die-tube is in the range of 0.05~0.15; push assistant level should be no less than 100%.

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TA18 高强钛管数控弯曲成形截面扁化研究

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摘 要：截面扁化是管材弯曲成形过程中不可避免的物理现象，而严重的截面扁化会影响弯管件的合理装配，从而制约其广泛应用。本文建立了考虑收缩应变比和弹性模量变化的钛管数控弯曲成形有限元模型，研究了不同几何条件和不同工艺条件下 TA18 钛管的截面扁化行为。结果表明：同时考虑收缩应变比和弹性模量变化规律可使截面扁化量发生改变，对变化规律无显著影响。获得了合理的几何、工艺参数范围。为研究 TA18 钛管的成形预测与控制并最终实现精确成形提供了依据。

关键词：钛管；数控弯曲；截面扁化；收缩应变比；弹性模量

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