Friction role in deformation behaviors of high-strength TA18 tubes in numerical control bending

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Abstract: In order to reveal the friction role in deformation behaviors of high-strength TA18 tubes in numerical control (NC) bending, a three dimensional (3D) elastic-plastic finite element (FE) model of high-strength TA18 tubes for whole process in NC bending was established based on ABAQUS code, and its reliability was validated by the experimental results in literature. Then, the bending deformation behaviors under different friction coefficients between tube and various dies were studied with respect to multiple defects such as wall thinning, wall thickening and cross section deformation. The results show that the wall thinning ratio and cross section deformation ratio increase with the increase of the friction coefficient between mandrel and tube $f_m$, or decrease of the friction coefficient between pressure die and tube $f_p$, while the friction coefficient between bending die and tube $f_b$ has no obvious effect on these. The wall thickening ratio decreases with the increase of $f_b$, $f_m$ or decrease of $f_p$. 

1. Introduction

Due to high strength/weight ratio, high pressure resistance, and long life, high-strength TA18 bent tubes have been increasingly used in many industries including aviation, aerospace and automobile as key lightweight components for gas and liquid transport. Among various bending methods such as compress bending, stretch bending and pushing bending, the numerical control (NC) bending is a feasible one for achieving stable bending of the high-strength TA18 tubes. However, the tube NC bending is a complex physical process with multi-factor coupling effect and multiple defects such as wrinkle, over thinning and cross section deformation with the inappropriate forming parameters used. Among many factors affecting tube bending deformation behaviors, the friction on various tube-die interfaces is a main factor. Thus, it is necessary to research the friction role in tube bending deformation behaviors.

In recent years, many researchers have studied tube bending deformation behaviors by analytical, experimental or numerical methods. Lu et al[1] derived some theoretical formulae including stress, wall thickness variation, cross section deformation, curvature radius of neutral layer and bending moment based on the plane strain assumption and exponent hardening law. Several bending related formulae such as wall thickness variation, cross section deformation, bending moment and stress distributions were deduced by Tang [2]. Liu et al[3,4] experimentally studied the effects of process parameters and various dies on wall thickness distribution and cross section deformation of thin-walled rectangular 3A21 aluminum alloy tube in rotary draw bending. The effects of temperature, bending speed and grain size on wall thickness variation, cross section deformation and springback of
AM30 magnesium alloy tube in rotary draw bending were investigated by experimental method in Ref.[5]. Fang et al.[6-8] established a three dimensional (3D) elastic-plastic finite element (FE) model of whole process of high-strength 21-6-9 stainless steel tube in NC bending, and revealed the effects of geometrical parameters, mandrel types/parameters and friction conditions on wall thickness variation and cross section deformation. Yang et al.[9] explored the effects of friction on bending behaviors of 5052O tube and 1Cr18Ni9Ti tube in terms of multiple defects such as wrinkling, wall thickness variation and cross section deformation by using explicit FE simulation combined with physical experiment. By embedding the variation in contractile strain ratio with deformation into FE simulation of Ti-3Al-2.5V tubes in NC bending, the prediction accuracy for wall thinning degree, cross section deformation degree and springback was improved in literature[10]. While up to now, the reported about the friction role in bending deformation behaviors of tube NC bending with respect to multiple defects is very few[8,9].

Thus, in this paper, a 3D elastic-plastic FE model of whole process of high-strength TA18 tubes in NC bending process was established based on ABAQUS code. Then, the effect laws of friction on wall thinning, wall thickening and cross section deformation were revealed.

2. Research methods

Based on the ABAQUS code, a 3D elastic-plastic FE model of whole process of high-strength TA18 tubes in NC bending was established as shown in Figure 1. The explicit algorithm was employed for bending and retracting process, while the implicit one was used for unloading process. The mechanical properties of high-strength TA18 tubes were obtained by uniaxial tension test in Ref.[11]. The classical coulomb friction model was used to describe the friction behavior between tube and dies. For unloading process, all tools were removed and a fixed boundary condition was applied to avoid the rigid motion. The detailed solutions process involved in FE modeling can be found in Ref.[12].

![Figure 1. 3D elastic-plastic FE model for high-strength TA18 tube in NC bending](image)

In order to validate the 3D elastic-plastic FE model of high-strength TA18 tubes in NC bending process, taking 9.525 mm×0.508 mm (diameter×wall thickness ) high-strength TA18 tubes as objects, the simulation for bending process was carried out based on the experimental conditions in literature [13]. The comparison between FE simulative and experimental results obtained in literature [13] as shown in Figure 2. It is found that the maximum value relative error of wall thinning ratio is 13.6%, while the one of cross section deformation ratio is 13.8%. Thus, the results show that the FE model is reliable, which can be employed to further investigate the deformation behaviors of high-strength TA18 tubes in NC bending under different friction conditions.
3. Results and discussion

The premise of tube NC bending is that there is no relative slip between clamp die and tube. So, the dry friction condition with no lubricant should be used. The wiper die is located backwardly to prevent the wrinkling, and the effect of friction between wiper die-tube interface on wall thickness change and cross section deformation can be neglected. Therefore, numerical study on the effect of friction on deformation behaviors of other interfaces such as bending die-tube ($f_b$), mandrel-tube ($f_m$) and pressure die-tube ($f_p$) are carried out by changing the friction coefficients from 0.05 to 0.45.

3.1. Effect of $f_b$ on wall thickness variation and cross section deformation

Figure 3 shows the effect of friction coefficient between bending die and tube $f_b$ on wall thickness variation and cross section deformation. It is can be seen from Figure 3 that the wall thinning ratio $\Delta t_o$ ($\Delta t_o=(t-t')/t \times 100\%$, where $t$ denotes initial tube wall thickness, $t'$ denotes minimum wall thickness after bending deformation) and cross section deformation ratio $\Delta D$ ($\Delta D=(D-D')/D \times 100\%$, where $D$ is initial tube outer diameter, $D'$ is vertical length of cross section after bending deformation) have no obvious variation with the increase of the friction coefficient between bending die and tube, while the wall thickening ratio $\Delta t_i$ ($\Delta t_i=(t''-t)/t \times 100\%$, where $t''$ denotes maximum wall thickness after bending deformation) decreases. The reason is that the bending die does not directly contact with the extrados of tube, which leads the acting force of bending die difficult to transfer from the intrados to the extrados of tube. Thus, the friction on this interface has little effect on the wall thinning. However, the tangential compression stress decreases with the increase of friction coefficient between bending die and tube, which makes the wall thickening decrease. The cross section deformation is mainly caused by the tangential stress of outer side because of the special boundary constraints in tube NC bending. Therefore the friction on bending die-tube interface also has no obvious effect on the cross section deformation.
Figure 3. Effect of $f_b$ on wall thickness variation and cross section deformation:
(a) wall thinning ratio; (b) wall thickening ratio; (c) cross section deformation ratio

3.2. Effect of $f_m$ on wall thickness variation and cross section deformation
Figure 4 shows that the effect of friction coefficient between mandrel and tube $f_m$ on wall thickness variation and cross section deformation. It is found that the wall thinning ratio and cross section deformation ratio increase with the increase of the friction coefficient between mandrel and tube, while the wall thickening ratio decreases. The main reason is that the tangential tensile stress at the extrados increases with the increase of the friction coefficient on this interface, which leads the wall thinning and cross section deformation increase. However, the larger the friction coefficient on this interface is, the smaller tangential compression stress is, which causes the wall thickening ratio decrease.

Figure 4. Effect of $f_m$ on wall thickness variation and cross section deformation:
(a) wall thinning ratio; (b) wall thickening ratio; (c) cross section deformation ratio

3.3. Effect of $f_p$ on wall thickness variation and cross section deformation
Figure 5 shows that the effect of friction coefficient between pressure die and tube $f_p$ on wall thickness variation and cross section deformation. As can be seen form Figure 5 that the friction coefficient on this interface has little effect on the wall thickness variation and cross section deformation. The maximum wall thinning ratio and cross section deformation ratio decrease with the increase of the friction coefficient between pressure die and tube, while the maximum wall thickening ratio increases.
These results are similar to those of the NC bending for 21-6-9 high-strength stainless steel tube [8]. The reason is that the pushing assistant role of pressure die is improved by the larger friction on this interface. The larger friction force decreases the tangential tensile stress at the extrados and increases the tangential compression at the intrados.

Figure 5. Effect of $f_p$ on wall thickness variation and cross section deformation: (a) wall thinning ratio; (b) wall thickening ratio; (c) cross section deformation ratio

4. Conclusions

Based on ABAQUS platform, a 3D elastic-plastic FE model of high-strength TA18 tubes in NC bending for whole process was established, and its reliability was validated by the experimental results in literature. Then, the bending deformation behaviors under different friction coefficients between tube and various dies were studied by using the model. The following conclusions can be drawn form this study:

(1) The wall thinning ratio and cross section deformation ratio have no obvious variation with the increase of the friction coefficient between bending die and tube, while the wall thickening ratio decreases.

(2) The wall thinning ratio and cross section deformation ratio increase with the increase of the friction coefficient between mandrel and tube, while the wall thickening ratio decreases.

(3) The wall thinning ratio and cross section deformation ratio decrease with the increase of the friction coefficient between pressures die and tube, while the wall thickening ratio increases.

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