Effect of process parameters on wall thinning of high strength 21-6-9 stainless steel tube in numerical control bending

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Abstract. Wall thinning, as one of the key defects determined directly the usability of the bent tube, should be strictly controlled. Elastic modulus changes with the plastic deformation and its influence the plastic forming quality of tube bending. To precisely predict the wall thinning of tube bending, a finite element (FE) model for numerical control (NC) bending of high strength 21-6-9 stainless steel tube (21-6-9-HS tube) was established considering the variation of elastic modulus. Using the model, the effects of process parameters on wall thinning of the 21-6-9-HS tube in NC bending were investigated. The results show that the variation of elastic modulus has no obvious effect on the change tendency of the wall thinning degree, but only increases the value of the wall thinning degree. The wall thinning degree enhances sharply at first, then occurs a platform deforming characteristics, and finally reduces abruptly from the bending section to the initial bending section, and it increases with the increase of the clearance of tube-bending die, the friction coefficient of tube-bending die and the friction coefficient of tube-wiper die or with the decrease of the clearance of tube-wiper die, but the increased degree is not significant in all conditions.

1. Introduction
Metallic tubes and tubular components have attracted increasing applications in various high-technology fields such as aviation, aerospace and automobile owing to the advantages of lightweight, material-saving and perfect buffer property [1]. High strength 21-6-9 stainless steel tube (21-6-9-HS tube), due to the special properties of high temperature and pressure resistance and excellent corrosion resistance, has become the preferred material for the above high-technology industries. Among various bending methods such as press bending, stretch bending, roll bending, the numerical control (NC) bending can achieve the 21-6-9-HS tube precision bending forming because of its advantages of precision, digitization and intellectualization. Compared with Al-alloy and common stainless steel tube, the 21-6-9-HS tube is more easily to produce various defects such as wall thinning, cross section distortion and springback in bending process due to the mechanical properties of the large yield strength, low elongation and high yield strength-to-elastic modulus ratio. Elastic modulus is an important mechanical property parameter that affects the plastic deforming quality of the 21-6-9-HS tube, and its change with the plastic deformation. The wall thinning will weaken the pressure-bearing capacity of the bent tube components and should be strictly controlled by adjusting process parameters in tube bending process so that it satisfies the requirement of aviation standard. Therefore, the effect of process parameters on wall thinning of the 21-6-9-HS tube in NC bending should be investigated.
Up to now, many works about wall thinning in tube bending have been carried out. E et al.[1] derived the formula of wall thinning for the rotary draw bending process considering the axial force based on the assumptions of plane strain, ideal rigid-plastic material and material incompressibility. Lu et al.[2] deduced several mathematical formulae such as stress/strain distributions, neutral layer curvature radius, wall thickness variation and cross section deformation using the plane strain assumption and exponent hardening law. Safdarian and Kord [3] experimentally studied the effects of process parameters on wall thinning and ovality of BS3059 steel tube in rotary draw bending. Kahanmouei and Fattahi [4] investigated the effects of the outer diameter-to-wall thickness ratio on wall thickness variation of the steel tube by using the hydraulic horizontal tube bender. The effects of bending velocity on wall thinning, wrinkling and springback of 6061-T4 thin-walled tube in NC bending were experimentally researched by Li et al. [5]. By finite element (FE) analysis, Fang et al. [6] studied the wall thickness variation under different geometrical parameters of the high strength TA18 tube in NC bending. Li et al. [7] numerically investigated the wall thinning behaviors of Al-alloy and stainless-steel tube in NC bending under different push assistant loading conditions. For the 21-6-9-HS tube, Fang et al. [8,9] established a FE model for NC bending of the 21-6-9-HS tube under the ABAQUS code and revealed the effects of friction conditions on wall thickness change and cross section deformation. However, the previous studies did not consider the variation of elastic modulus with plastic deformation. This will affect the accuracy of FE simulation to some extent, especially for the 21-6-9-HS tube with high yield strength-to-elastic modulus ratio. Thus, in this study, a three-dimensional (3D) FE model for NC bending of the 21-6-9-HS tube is established under the ABAQUS platform considering the variation of elastic modulus. Using the model, the effects of process parameters on wall thinning of the 21-6-9-HS tube in NC bending are investigated. The results have an important theoretical significance and practical application value for tube NC bending.

2. 3D-FE model of the 21-6-9-HS tube in NC bending and its validation

Considering the variation of elastic modulus, the 3D-FE model for NC bending of the 21-6-9-HS tube was established based on the code of ABAQUS with the bent tube specification of 9.53 mm × 0.51 mm × 28.59 mm (outer diameter × wall thickness × bending radius), as shown in Fig.1. The constitutive equation considering the varied elastic modulus was implemented into the FE model for bending tube and retracting mandrel by user subroutine VUMAT based on the ABAQUS/Explicit platform. Since springback was regarded as a pure elastic unloading process, the constitutive equation considering the varied elastic modulus was embedded into the FE model for springback by the user subroutine UMAT based on ABAQUS/Standard platform. The detailed modeling process can be found in literature [10].

To verify the dependability of the FE model, the NC tube bending experiments were implemented on the tube bender SB-12 × 3A-2S. Fig.2 shows the comparison between the simulated results and experimental ones. It can be seen from that the FE simulated results with varied elastic modulus is closer to the experimental results, and the maximum relative error is about 7.72%. Thus, the FE model considering the varied elastic modulus is dependable, which can be further applied to reveal the laws of wall thinning under different process parameters for the 21-6-9-HS tube during NC bending.
3. Results and discussion

Fig.3 shows effect of clearance between tube and bending die \( C_b \) on wall thinning degree of the 21-6-9-HS tube in NC bending with or without considering the variation of elastic modulus. As can be seen from that the variation of elastic modulus has no obvious effect on the variation tendency of the wall thinning degree from the bending section to the initial bending section, however it can cause the wall thinning degree to increase.

For a given clearance \( C_b \), the wall thinning degree enhances quickly in the neighborhood of the bending plane, then scarcely varies, and finally reduces sharply near the initial bending plane. The wall thinning degree increases with the increase of the clearance between tube and bending die. This is because that the smaller clearance \( C_b \) facilitates the tube material to flow from straight section of the tube to bending deformation zoon. Thus, the wall thinning degree of outer side wall thickness of the tube is small. With increasing the clearance \( C_b \), the positive applied force of the bending die on the tube decreases, which causes the wall thinning degree to increase.

Fig.4 shows effect of clearance between tube and wiper die \( C_w \) on wall thinning degree of the 21-6-9-HS tube in NC bending with or without considering the varied elastic modulus. It is found that the variation of elastic modulus has no obvious effect on the variation tendency of the wall thinning degree from the bending section to the initial bending section, but it can make the wall thinning degree increase.

With the increase of the clearance \( C_w \), the wall thinning degree of outside wall thickness of the tube decreases. Especially when the clearance \( C_w \) increases from 0.1 mm to 0.2 mm, the wall thinning is more obvious. When the clearance \( C_w \) continues to increase, the wall thinning degree hardly changes. This is because that the friction force of the wiper die on the tube reduces with increasing the clearance.
$C_w$, which leads to decrease the tangential tensile stress. Thus, the wall thinning degree reduces. When the clearance $C_w$ is more than 0.2 mm, with increasing the clearance $C_w$, the friction force of the wiper die on the tube has no significant change. Therefore, the wall thinning degree has no obvious change.

Fig.4 Effect of $C_w$ on wall thinning: (a) with varied elastic modulus; (b) with constant elastic modulus

Fig.5 shows effect of friction coefficient between tube and bending die $f_b$ on wall thinning degree of the 21-6-9-HS tube in NC bending with or without considering the variation of elastic modulus. It is discovered that the variation of elastic modulus has no obvious effect on the variation tendency of the wall thinning degree from the bending section to the initial bending section, however it can lead to increase the wall thinning degree.

For a specific friction coefficient $f_b$, the distributions of the wall thinning degree from the bending section to the initial bending section are similar to those influenced by the clearance between tube and dies. Namely, the wall thinning degree enhances sharply at first, then occurs a platform deforming characteristics, and reduces abruptly in the end from the bending section to the initial bending section. With the increase of the friction coefficient $f_b$, the wall thinning degree of outside wall thickness of the tube hardly changes. This is because that the bending die contacts with the inner side of the tube, but not the outer side of the tube, which leads to transfer the acting force of bending die on the tube very difficult from the inner side to the outer side of the tube. Therefore, the friction coefficient on this interface has little influence on the wall thinning degree.

Fig.6 shows effect of friction coefficient between tube and wiper die $f_w$ on wall thinning degree of the 21-6-9-HS tube in NC bending with varied and constant elastic modulus. As observed in Fig.6, the
variation of elastic modulus has no obvious effect on the variation tendency of the wall thinning degree from the bending plane to the initial bending plane, but it can cause the wall thinning degree to increase.

When the friction coefficient $f_w$ in this interface increases from 0.05 to 0.5, the wall thinning degree in the extrados increases, but the increased degree is not obvious. The reasons are that increasing the friction coefficient in this interface causes the tangential tensile stress to augment, which makes the wall thinning degree augment. On the other hand, the wiper die does not contact directly with the outer side of the tube, which causes the applied force of the wiper die on the tube difficult to transfer from the inner side to the outer side of the tube. Therefore, the synthetic action for the both makes the increase of the wall thinning degree be not obvious.

Fig.6 Effect of $f_w$ on wall thinning: (a) with varied elastic modulus; (b) with constant elastic modulus

4. Conclusions
Considering the variation of elastic modulus, the 3D-FE model for the NC bending of the 21-6-9-HS tube was applied to explore the effects of process parameters on wall thinning. The main conclusions are as follows:

(1) The variation of elastic modulus has no obvious effect on the variation tendency of the wall thinning degree from the bending section to the initial bending section, but it can make the value of the wall thinning degree increase.

(2) The wall thinning degree enhances sharply at first, then occurs a platform deforming characteristics, and reduces abruptly in the end from the bending section to the initial bending section.

(3) The wall thinning degree increases with the increase of the clearance $C_b$, the friction coefficient $f_b$ and the friction coefficient $f_w$ or with the decrease of the clearance $C_w$, but the increased degree is not significant in all conditions.

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References
[1] E, D.X., Liu, Y.F., Feng, H.B. (2010) Deformation analysis for the rotary draw bending process of circular tubes: stress distribution and wall thinning. Steel Res. Int., 81:1084-1088.
[2] Lu, S. Q., Fang, J., Wang, K. L. (2016) Plastic deformation analysis and forming quality prediction of tube NC bending. Chinese J. Aeronaut., 29:1436-1444.
[3] Safdarian, R., Kord, A. (2019) Experimental investigation of effective parameters in the tube rotary bending process. Mater. Res. Express, 6: 1-12.
[4] Kahnamouei, T. J., Fattahi, A. M.(2015) Experimental and numerical investigation of friction coefficient effects on defects in horizontal tube bending process. J. Theor. Appl. Mech., 53:
837-846.

[5] Li, H., Yang, H., Tian, Y.L., Shi, K.P. (2012) Experimental study on bendability of thin-walled 6061-T4 tube under different bending velocities. Appl. Mech. Mater., 184-185: 196-200.

[6] Fang, J., Liang, C., Lu, S.Q., Wang, K.L. (2018) Effect of geometrical parameters on forming quality of high-strength TA18 titanium alloy tube in numerical control bending. Trans. Nonferrous Met. Soc. China, 28: 309-318.

[7] Li, H., Yang, H., Zhan, M., Kou, Y. L. (2010) Deformation behaviors of thin-walled tube in rotary draw bending under push assistant loading conditions. J. Mater. Process. Technol., 210:143-158.

[8] Fang, J., Lu, S.Q., Wang, K.L., Yao, Z.J. (2015) Three-dimensional finite element model of high strength 21-6-9 stainless steel tube in rotary draw bending and its application. Indian J. Eng. Mater. Sci., 22:142-151.

[9] Fang, J., Lu, S.Q., Wang, K.L., Yao, Z.J. (2015) Deformation behaviors of 21-6-9 stainless steel tube numerical control bending under different friction conditions. J. Cent. South Univ., 22:2864-2874.

[10] Ouyang, F., Lu, S.Q., Fang, J., Wang, K.L., Ouyang, D.L. (2020) Effect of geometrical parameters on forming quality of 21-6-9 tube in rotary draw bending under condition of variable elastic modulus. J. Plasticity Eng., 27: 27-37.