Springback compensation of high strength 21-6-9 tube after NC bending

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Abstract: In order to achieve high strength 21-6-9 (HS-21-6-9) tube numerical control (NC) bending precision forming, the springback law and compensation should be studied for the HS-21-6-9 tube NC bending. By using a finite element (FE) simulation method, the effects of bending angle $\theta$ on springback angle $\Delta \theta$ and springback radius $\Delta R$ of the HS-21-6-9 tube NC bending were investigated. The results show that the $\Delta \theta$ increases linearly with the increase of the $\theta$, and the relationship between the $\Delta \theta$ and the $\theta$ can be described as $\Delta \theta=2.47179+0.02208 \theta$. The $\Delta R$ decreases along the curve with the increase of the $\theta$, and the relationship between the $\Delta R$ and the $\theta$ can be described as $\Delta R=33.86587 \theta^{-0.64431}$. The compensation methodology is proposed considering the $\Delta \theta$ and the $\Delta R$ simultaneously, and the viability of the methodology is validated by an example.

1. Introduction
The application of high strength 21-6-9 (HS-21-6-9) tube is becoming increasingly extensive in aviation, aerospace and other high technology fields because of its advantage of high strength, corrosion resistance and oxidation resistance[1]. Among all kinds of bending methods, the numerical control (NC) bending, under multi-tool constraints as shown in Fig.1, is the most effective method to fabricate bent-tube components owing to the characteristics of high precision, high efficiency, and digitization and so on. After the dies are removed, the elastic strain will release, namely, springback will happen. The springback directly affects the forming precision of the bent-tube components, and influences the connection and sealing property with other components as well as the internal structure compact. This phenomenon is particularly significant for tubes with high ratio of the yield strength to Young’s modulus, such as HS-21-6-9 tubes. Therefore, in order to achieve tube precision bending forming, the springback law and compensation after tube bending have got more and more attention.

At present, a lot of studies on the springback prediction of tube bending have been conducted by using theoretical analysis, experimental research and numerical simulation. Zhan et al.[2,3] deduced the springback model for welded tube and Ti-alloy tube bending under the static equilibrium condition. Lu et al.[4] derived the springback angle and radius of tube bending based on the virtual work principle and the length of neutral layer remained unchanged before and after springback. By experiments, Li et al.[5] studied the effects of forming parameters on springback of aluminum alloy
tubes NC bending. Han et al.\[6\] experimentally studied the effects of the bending angle, weld line, diameter-thickness ratio and relative bending radius on springback of advanced high-strength steel DP590 welded tubes in NC bending. By the numerical simulation analysis, Shahabi and Nayebi \[7\] investigated the effect of four material hardening models on springback of titanium alloy tube in NC bending. Liao et al.\[8\] studied the twist springback prediction of asymmetric tube in NC bending with different constitutive models by experimental and numerical methods. The springback characterization and behaviors of high-strength titanium alloy tube in NC bending were addressed using theoretical, experimental and numerical methods, and the two level springback compensation method was presented by Li et al.\[9\]. Recently, for the HS-21-6-9 tube bending springback problems, Fang et al.\[10\] studied the effects of process parameters on springback behaviors of the HS-21-6-9 tube in NC bending using numerical simulation combined with multi-parameter sensitivity analysis.

However, the aforementioned studies mostly focus on the springback prediction of tube bending such as titanium alloy, aluminum alloy and steel tubes bending springback. For the springback compensation or control of tube bending, the reports are a little. Therefore, in this work, the effects of bending angle on springback angle and radius of the HS-21-6-9 tube NC bending were firstly investigated. Then, the compensation method was proposed with considering springback angle and springback radius simultaneously, and the feasibility of the method was validated by an example. The results and methods have important theory and actual value for tube bending springback prediction and control.

![Fig.1. Schematic diagram of NC tube bending](image)

\[2. \textbf{Research methods} \]

On the basis of the practical tube NC bending forming process, an explicit/implicit elastoplastic 3D-FE model of the whole NC bending process including bending tube, retracting mandrel and springback for the HS-21-6-9 tube with the bent-tube specification of 15.88 mm × 0.84 mm × 47.64 mm (diameter D × wall thickness t × bending radius R) is established under the ABAQUS code as shown in Fig.2. The explicit algorithm was applied to bending tube and retracting mandrel operation, while the implicit one was used for springback computation. The simulation results of bending tube and retracting mandrel in ABAQUS/Explicit were directly imported into ABAQUS/Standard. The geometrical nonlinearity was contained, and the specified damping factor was employed for stabilizing implicit iteration procedure during springback analysis. Double precision was used for the bending stage and the single precision for the springback analysis. The mass scaling factor of 2000 was applied to improve the computation cost with neglected inertia effect by using the convergence analysis in bending simulation. The element sizes of 1.5mm×1.5mm and 2mm×2mm were used to the tube and die surfaces, respectively. The detailed modeling process and forming parameters such as process parameters, geometrical parameters and material parameters can refer to the literature\[10\].

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In order to validate the dependability of the 3D-FE model, the experiments were conducted on the NC tube bender SB-12×3A-2S. The experimental parameters are as follows: the tube diameter D and wall thickness t of the HS-21-6-9 tube are 6.35 mm and 0.41 mm, respectively; the bending radius R is 20 mm; the bending angle θ are 30°, 60°, 90°, 120°, 150 and 180°, respectively; the bending speed ω is 0.4 rad/s; the push assistant speed of the pressure die Vp is 8mm/s; and the dry friction condition is employed to the contact interfaces.

Fig.3 shows the comparison between experiment and simulation results of the HS-21-6-9 tube after NC bending. It is found that the FE simulation results are agreement with the experiment ones. The maximum relative error of the springback angle is 15.55%, and the average relative error of the springback angle is 10.12%. Therefore, the 3D-FE model is dependable, which can be utilized to investigate the springback behavior and compensation of the HS-21-6-9 tube after NC bending.

3. Results and discussion

Effects of bending angle on springback angle and radius. Fig.4 shows the effects of bending angle θ on springback angle Δθ and radius ΔR for the HS-21-6-9 tube NC bending. As shown in Fig. 4(a), the Δθ increases with the increase of the θ when the θ changes with the scope of 15°-180°. This is because that accumulated elastic deformation increases with the increase of the θ under the same bending radius, which causes the Δθ to increase. It also can be seen form Fig.4(a) that, the fitting curve between the Δθ and the θ has a good agreement with simulation curve, and the correlation coefficient r is 0.98985. This shows that a significant linear relation is existed between the Δθ and the θ when the θ is with the scope of 15°-180°, and the fitting equation can be obtained as Δθ=2.47179+0.02208θ. Therefore, it can quickly and effectively compensate the forming angle by using the linear relation between the Δθ and the θ in engineering application, and adopting over bending method to achieve bent-tube precision forming.
Fig. 4(b) shows that the $\Delta R$ decreases with increasing of the $\theta$. When the $\theta$ is less than 60°, the $\Delta R$ decreases rapidly with the increase of the $\theta$. When the $\theta$ is more than 60°, the decrease tendency of the $\Delta R$ becomes slow with the increase of the $\theta$. As also can be seen from Fig. 4(b) that, the fitting curve between the $\Delta R$ and the $\theta$ has a good agreement with simulation curve, and the correlation coefficient $r$ is 0.98769. The fitting equation can be drawn as $\Delta R=33.86587\theta - 0.64431$. Thus, it can quickly predict the forming radius by using the relationship between the $\Delta R$ and the $\theta$ in engineering application, which can guide the mold design to effectively control the $\Delta R$.

Springback compensation of the HS-21-6-9 tube NC bending. Since the springback phenomenon is very obvious in NC bending process of the HS-21-6-9 tube, to obtain the precision bent-tube parts, both the $\Delta \theta$ and $\Delta R$ should be compensated simultaneously. According to the above and previous research works[10] obtained knowledge about the springback behaviors of the HS-21-6-9 tube in NC bending, a simultaneous compensation method for the $\Delta \theta$ and $\Delta R$ is proposed. Fig. 5 shows the springback compensation method for the HS-21-6-9 tube in NC bending. The details of the processes are as follows:

(1) For the given bent-tube specification of the HS-21-6-9 tube, namely, tube diameter $D$, wall thickness $t$, bending radius $R$ and $\theta$, the stable bending forming conditions including the reasonable die set conditions and process parameters should be obtained with wrinkling free and allowed tolerance of wall thinning and cross section distortion degrees.

(2) Via explicit/implicit FE simulation, the $\Delta \theta$ and $\Delta R$ are obtained, and the bending forming conditions should be modified by compensation for the $\Delta \theta$ and $\Delta R$ as

$$\theta_1 = \theta + \Delta \theta.$$  \hfill (1)

$$R_1 = R - \Delta R.$$  \hfill (2)

Where $\theta$, $R$ are the designed bending angle and radius, respectively, $\theta_1$, $R_1$ are the actual bending angle and radius after the first modification forming conditions, respectively.

(3) Via explicit/implicit FE simulation, the actual bending angle $\theta_2$ and radius $R_2$ are obtained under the compensation forming conditions of the $\theta_1$ and $R_1$. Then, the angle error $E_\theta$ and radius error $E_R$ are obtained comparison with the designed bending angle and radius as

$$E_\theta = |\theta_2 - \theta|.$$  \hfill (3)

$$E_R = |R_2 - R|.$$  \hfill (4)

If the bending tolerance is satisfied a precision requirement, then the springback compensation conditions are implemented, viz., this bending forming conditions can be regarded as the actual
forming conditions for the HS-21-6-9 tube in NC bending. Otherwise, the next step is needed as

\[ \theta_{l+1} = \theta_l \pm E_\theta, \quad (5) \]

\[ R_{l+1} = R_l \pm E_R. \quad (6) \]

Where \( \theta_l, R_l \) are the actual bending angle and radius after the \( l \)th modified forming conditions, respectively; \( \theta_{l+1}, R_{l+1} \) are the \((l+1)\)th bending forming conditions.

(4) Repeating the procedure 3 until the bending tolerance is satisfied the precision requirement.

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The above method has been used to the springback compensation of the HS-21-6-9 tube in NC bending with the specification of 15.88 mm × 0.84 mm. The desired bending angle and radius are 180° and 47.64 mm, respectively. The bending tolerance of the bending angle and radius are 0.1° and 0.1 mm, respectively. The details of the springback compensation procedures are as follows:

(1) For the given bent-tube specification of the HS-21-6-9 tube, the stable bending forming conditions refers to the literature [11].

(2) Via explicit/implicit FE simulation, the \( \Delta \theta \) and \( \Delta R \) are obtained as 6.446° and 1.193 mm, respectively. And the bending forming conditions are modified as
\[ \theta_1 = \theta + \Delta \theta = 180^\circ + 6.446^\circ = 186.446^\circ. \] (7)

\[ R_1 = R - \Delta R = 47.64 - 1.193 = 46.447 \text{ mm}. \] (8)

(3) Via explicit/implicit FE simulation, the actual bending angle \( \theta_2 \) and bending radius \( R_2 \) under the modified forming conditions are obtained as 179.929° and 47.574 mm, respectively.

(4) The bending forming tolerance \( E_\theta \) and \( E_R \) are calculated by formulae (3) and (4).

\[ E_\theta = |\theta_2 - \theta| = |179.929^\circ - 180^\circ| = 0.071^\circ < 0.1^\circ. \] (9)

\[ E_R = |R_2 - R| = |47.574 - 47.64| = 0.066 \text{ mm} < 0.1 \text{ mm}. \] (10)

Thus, the precision of the bent-tube part satisfies the requirement under the forming conditions of the actual bending angle of 186.446° and the actual bending radius of 46.447 mm. The qualified bent-tube part is obtained with the bending angle of 179.929° and the bending radius of 47.574 mm.

4. Conclusions
The springback behaviors and compensation of the HS-21-6-9 tube NC bending were investigated by using a FE simulation method. The main results are as follows:

(1) The \( \Delta \theta \) increases linearly with the increase of the \( \theta \), and the relationship between the \( \Delta \theta \) and the \( \theta \) can be described as \( \Delta \theta = 2.47179 + 0.02208 \theta \).

(2) The \( \Delta R \) decreases along the curve with increasing of the \( \theta \), and the relationship between the \( \Delta R \) and the \( \theta \) can be described as \( \Delta R = 33.86587 \theta - 0.64431 \).

(3) The simultaneous compensation method for the \( \Delta \theta \) and the \( \Delta R \) is proposed, and the reliability of the method is verified by an example.

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