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Coupled thermo-mechanical FE simulation of unloading cooling springback in NC heating bending of large diameter thin-walled commercial pure titanium tube

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Abstract

A new FE model of unloading cooling springback in the NC heating bending of large diameter thin-walled commercial pure titanium tube was developed by combination of stress-strain field and temperature field. With the commercial pure titanium tube of Φ50.8×t0.508×R101.6 mm as a representative component, the springback behaviours under different processing conditions were investigated. The results show that: 1) The springback angle increases slowly along with temperature increasing. With the temperature at 180-250 °C, the springback angle is least. 2) The heating temperature has certain influence on the cross section distortion. With temperature at 180-300 °C, forming quality is better. 3) The mandrel diameter has important influence on the cross section distortion. With the increasing of the mandrel's diameter, cross section distortion rate and outside deformation is more uniform.

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Keywords: Tube bending; Heating forming; Unloading cooling springback; Processing parameters; Titanium tube

1. Introduction

Pure titanium tubes have the property of light weight, high strength and corrosion-resistant. With the research and development of new domestic aircraft, lightweight components will be widely applied. Large diameter thin-walled commercial pure titanium bent tubes are widely used in the pneumatic system of commercial airplanes

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(Wang, 2006). However, due to the pure titanium tube forming with anisotropy, large deformation resistance, limited elongation and remarkable springback at room temperature (Richard, 2002), it makes the precise forming difficult (MacKenzie, 2007). NC (Numerical Control) heating tube bending is based on the NC tube bending technique and assembled with heating equipment（Fig. 1(a)）to achieve the goal of heating and bending tubes. On account of high machining accuracy, good controllability, suitable for material of high precision plastic forming, NC heating tube bending has broad development prospects of difficult deformation materials of high precision plastic forming. It is urgent to develop advanced technology of large diameter thin-walled pure titanium tube NC heating bending.

However, when finished the bending process, the elastic deformation of the elastic recovery and superimposition effect coupled with unloading makes the bending radius increase and bending Angle decrease, which called springback phenomenon (Zhan, 2004). The springback is one of the key problems affecting the forming precision of tube bending (Fig. 1(c)). When the springback angle is larger than the permitted error, the geometry and shape precision can't achieve the requirement of the qualified (Ruijie, 2008). Therefore, to analysis, predict and reasonably control the springback of thin-walled tube NC heating bending has become an important subject needed to be solved for the research and development of the precision forming technology of thin-walled tube NC heating bending.

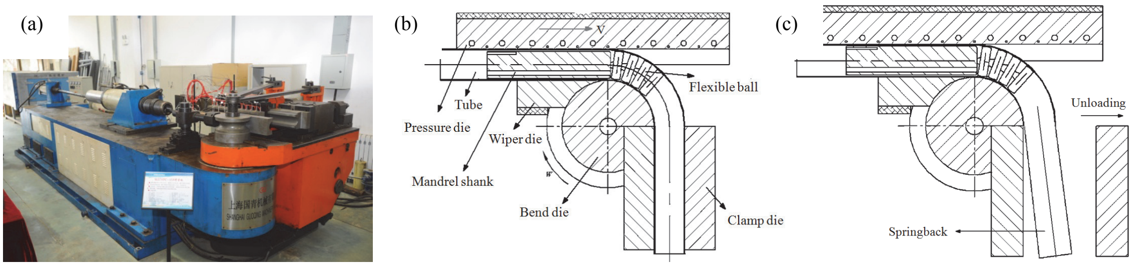

Fig.1. Process of large diameter thin-walled pure titanium tube NC heating bending. (a) The NC heating bending equipments, (b) NC heating bending process, (c) springback of the NC heating bending process.

Up to now, great efforts have been conducted on the springback of the sheet metal after plastic deformation by using experimental, analytical and numerical approaches. However, the domestic study of CNC hot bending are just getting started, mainly to focus on die heating, temperature control and uneven temperature field of CNC hot bending forming. Zhao et al. (2009) set up the 3D FEM model of ∅50×t1×R75 mm (outer diameter D×wall thickness t×centreline bending radius R) Titanium alloy tube based on ABAQUS including The heat transferring process and tube bending process and made the exploratory study on the effects of different bending speed, thrusting speed and uneven temperature field upon tube forming quality. Wu et al. (2008) simulated the process of Φ50.8×0.5×R101.6 mm pure titanium tube heating bending based on ANSYS and got the effects of temperature. Zhang et al. (2011) studied on large diameter thin-walled CP-Ti tube bending process and considered different processing conditions, which found that wrinkling is the primary behaviour for the LDTW CP-Ti tube which affected by the mandrel shank diameter and the clearance between wiper die and tube. At present, the domestic scholars haven't studied the springback process of large diameter thin-walled titanium heating tube bending. In this paper，using large diameter thin-walled commercial pure titanium tube with Φ50.8×t0.508×R101.6 mm as objective, build the model of unload cooling springback based on the ABAQUS, simulate and analyze the whole process and get the temperature's effect on the springback.

2. FE modeling of unloading cooling springback

The whole heating bending process is completed by mutual coordination of multiple dies, such as bending die, pressure die, mandrel shank, wiper die and clamp die, etc. The front end of the titanium tube is conditioned by clamping die and bending die, meanwhile the other end of the titanium tube is conditioned closely by pressure die and wiper die. After fitting the tube in equipment, the pressure die and mandrel shank should be heated to the right temperature and keep warm for a while, then start the equipment to bend the tube, finally unload and cool. Based on the method described by Wang et al. (2009) and the experimental plan, a series of 3D-FE models are established under FE platform ABAQUS to simulate the whole process of the NC heating bending of large diameter thin-walled commercial pure titanium tube (Fig. 2).

2.1. FE modeling of heat transferring

Based on ABAQUS/Standard, the FE model of heat transferring adopts short transient step analysis, while heat transfer analysis is performed by separating geometry into diffusion heat conduction unit. The material of thin-walled tube is commercial pure titanium (Table 1), while the material of dies is Cr12MoV and aluminium bronze. The factors of the model are listed in Table 2. During the process, there is not only the heat conduction between the tube and dies but also heat convection and heat radiation which should be considered. Convective heat transfer coefficient is set as $20\,w/m^2\cdot k$ and thermal emissivity is set as $0.7\,w/m^2\cdot k^4$. In the process of actual heating, electric heating rods are used to insert pressure die and mandrel shank for heating them to achieve reasonable temperature. The heating holes uniformly distributed in the pressure die and mandrel shank are set as plane heat source.

Table 1. Material factors of commercial pure titanium tube.

Temperature T/°C	20	100	200	300	400	500	600
Specific heat capacity c/J(Kg.K)$^{-1}$	544	544	628	670	712	754	837
Thermal conductivity λ /W(m.K)$^{-1}$	16.33	16.33	16.33	16.75	17.17	18	/
Coefficient of thermal expansion α /10^{-6}K^{-1}	/	8	8.6	9.1	9.25	9.4	9.8

Table 2. Factors of the FE model.

Component	Material	Mesh type
Tube	Commercial pure titanium tube	DS4
Bend die	Cr12MoV	DC3D4, DC3D8
Clamp die	Cr12MoV	DC3D8
Wiper die	Aluminium bronze	DC3D4
Pressure die	Cr12MoV	DC3D4
Mandrel shank	Aluminium bronze	DC3D4

2.2 FE modeling of NC heating bending

Due to the thermal and force coupling problem, it is found that FE modelling of NC heating bending should be built based on ABAQUS/Explicit calculator, setting as dynamic, temp-displacement and explicit (Fig. 3). In the bending model, the tube is set as shell element so as to save time, while all of the bending dies are set as rigid bodies and shown as curved surface. Because dies and tubes are Plane symmetric, the model uses half tube in order to improve the computational efficiency.

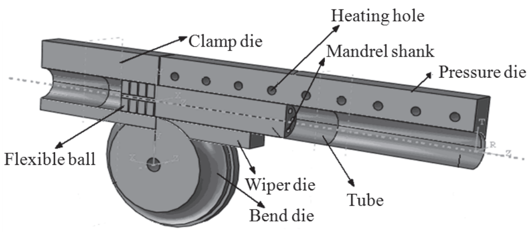

Fig.2. 3D-FE model of the NC heating bending with multiple dies.

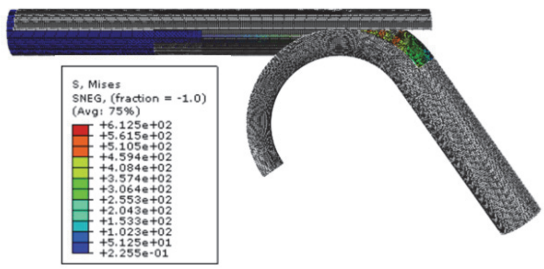

Fig.3. FE simulation of NC heating bending.

2.3 FE modeling of unload cooling springback

When establishing FE model of springback, it is acquiescent to export the heating bending result of the last frame, which inherited the relevant units and material information. The type of springback calculating forming step should be set as Static and General. Due to the large amount of springback of the titanium tube, Nlgeom should be set as On. In order to control model's stability, FE model of springback uses dissipated energy fraction defaulted by system and Specify damping factor 0.0002 to achieve convergence. Initial increment size is 0.01 and maximum increment size is 100, while minimum increment size is 1E-005 and maximum increment step number is 1.

There is only the titanium tube in the FE model of springback, so contact and friction needn't be considered. However, the boundary conditions must be defined. After unloading, the tube achieves static equilibrium under the action of own stress. Therefore, it is necessary to exert enough constraints to avoid rigid displacement (Fig. 4). In the springback step, the degree of freedom on translational direction and rotation direction should be released to achieve the tube's freely deformation. Because of half-tube modelling, it's necessary to impose boundary conditions on the tube's symmetric surface. Then the Stress and strain state after bending should be given to the tube in the springback model and cooling time is set as 1500 s. Finally the FE model of unloading springback is established (Fig. 5).

2.4 verifying reliability of FE model

Based on the ratio of pseudo strain energy (ALLAE) to internal energy (ALLIE), the reliability of the model is verified and evaluated. Through verification, ALLAE/ALLIE curve (Fig. 6) shows that the model's hourglass is light. Therefore the FE model of unloading cooling is reliable.

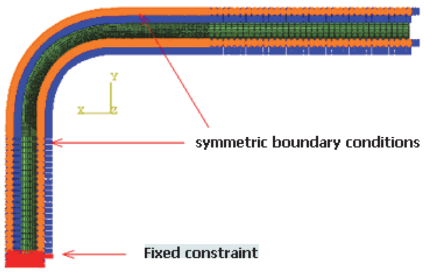

Fig.4.Boundary conditions.

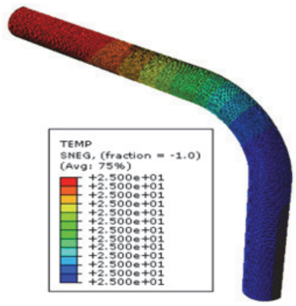

Fig.5. FE model of unloading cooling springback.

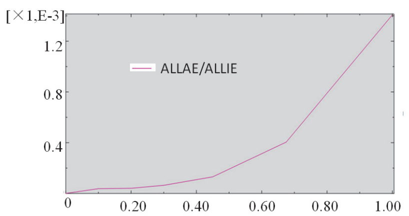

Fig.6. ALLAE/ALLIE curve of the FE model.

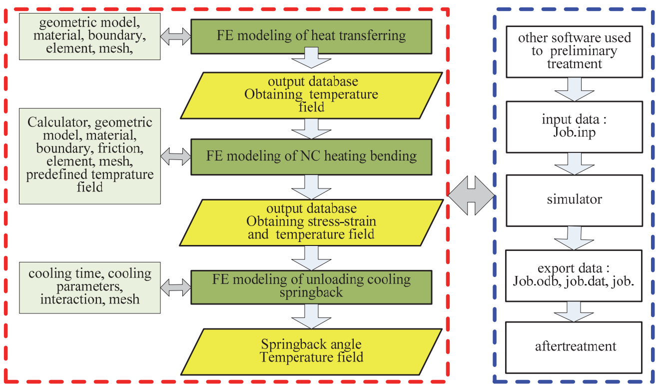

Fig.7. Whole process flow chart of FE modeling of NC unloading cooling springback.

3 Results and discussion

Based on the FE model of unloading cooling springback of large diameter thin-walled commercial pure titanium tube, different temperature sections and different values of mandrel diameter are considered to simulate the process of unloading cooling springback. The simulated results are list in table 3(bending angle=90°).

As is shown in Fig. 9, the springback angle is much smaller as a result of wrinkling occurred on the inside wall when bent at room temperature. With the increase of temperature, the pure titanium could get larger ductility and better formability leading to material flowing easier. When the temperature is between 150 and 180 °C, more material takes part in deformation and more elastic deformation would be cumulated. As a result, the springback angle rises with temperature increasing. When the temperature is between 180 °C and 250 °C, yield strength and ultimate strength has a significant decreasing which accompanied by softening material. Therefore, the springback angle decreases with temperature increasing. However, the value of springback is not only related to yield strength but also elasticity modulus. When bending radius set as fixed value, it is proportion to the yield strength and inversely proportion to the elasticity modulus, whose mutual coordination affects the springback angle. It's clear that the springback angle keeps increasing when temperature is upon 250 °C. To sum up, the smallest springback angle would be achieved at the temperature of 180 to 250 °C and the diameter of mandrel has significant effects on the value of springback. Fig.10 shows the cross section distortion rates of different temperature while mandrel diameter is 49.68 mm. The cross section distortion rate decreases gradually with temperature increment and also changes nonlinearly with different location. Compare the cross section distortion of cool bending with heating bending, and it's clear that heating can make the cross section distortion more uniform. As a result, good deformation quality could be achieved which the heating temperature is between 180 and 300 °C.

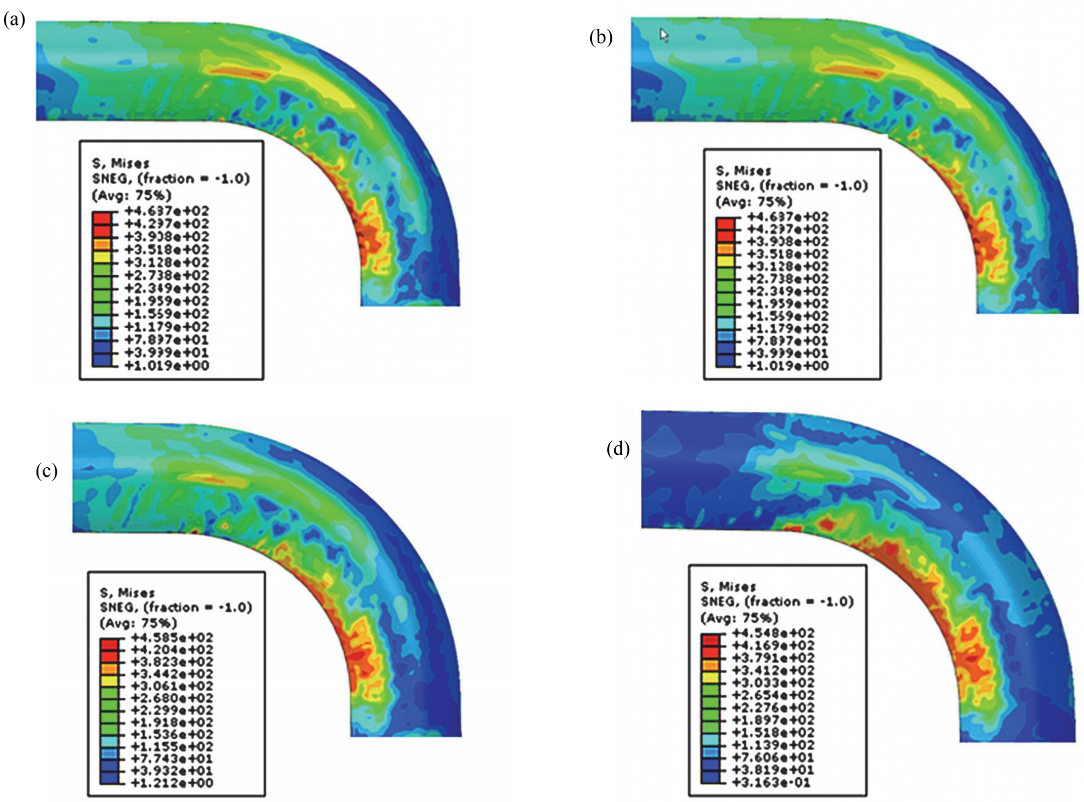

Fig.8.Process of springback. a) Springback angle =0° (0%), b) Springback angle =0.538° (30%), c) Springback angle =1.251°(60%) , d) Springback angle =2.767°(90%).

Table 3. Springback angle of different temperature and diameter.

temperature (°C)	49.64 mm Springback angl（°）	49.60 mm Springback angl（°）	49.68 mm Springback angl（°）
25	0.3074	0.3384	0.0820
120-150	0.9099	0.9681	1.0432
150-180	2.2159	1.1523	1.4271
180-220	1.2137	0.1718	1.4820
220-250	0.5397	2.7667	1.6568
250-300	1.6731	1.5778	1.7936
300-400	2.0728	2.0689	1.9261

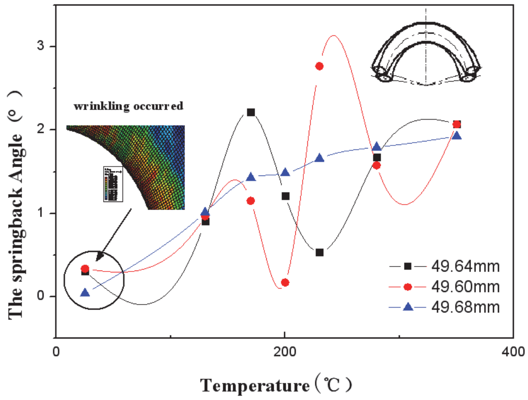

Fig.9.Springback angle of different temperature and diameter.

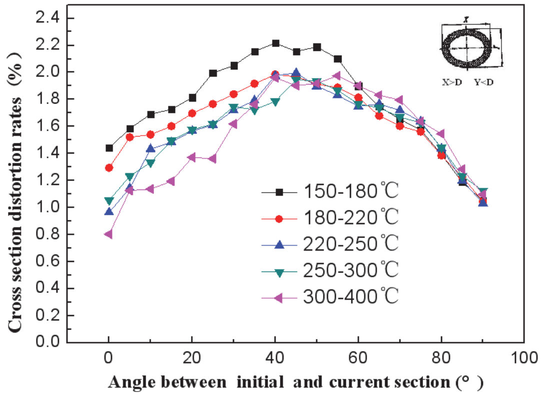

Fig.10. Cross section distortion rates of different temperature (mandrel diameter =49.68 mm).

The result of tube unloading springback should be imported into cooling FE model to simulate the process of heat dissipation. The method can display non-uniform stress field and non-uniform temperature field which is always changing during the process of springback. Fig.11 shows the cooling process of large diameter thin-walled commercial pure titanium tube, while temperature is 150 °C, bending angle is 90° and mandrel diameter is 49.60 mm.

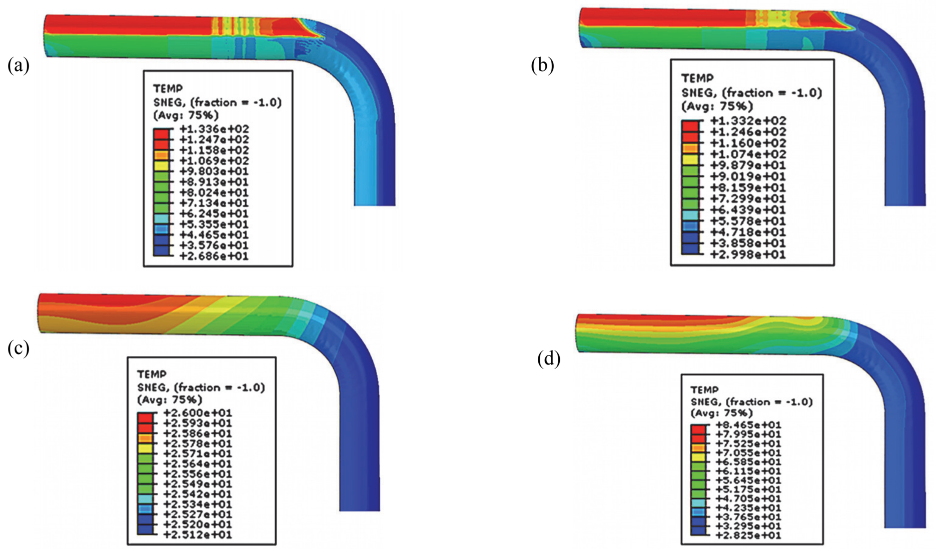

Fig.11. Process of cooling. a) cooling time =0, b) cooling time =30%, c) cooling time =60% ,d) cooling time =90%.

4. Conclusion

In this work, using large diameter thin-walled commercial pure titanium tube with Φ50.8×t 0.508×R101.6 mm as objective, the FE model of unloading cooling springback is built based on the ABAQUS. After establishing the FE model and simulating the whole process, the effects of different parameters on the unloading cooling springback are studied seriously. Through analyzing the effects of process parameters on springback, the results show that: In the conditions of the same bending angle, the springback angle of the big diameter thin-wall titanium tube increases slowly along with temperature increasing. With the temperature at 180-250 °C, the springback angle is least. In the low temperature range, the diameter of mandrel has relatively large effect on the springback angle with the same heating temperature. The heating temperature on bending springback process has certain influence on the cross section distortion. With temperature at 180-300 °C, forming quality is better. The mandrel diameter has important influence on the cross section distortion. Under the same heating condition, with the increasing of the mandrel's diameter, cross section distortion t rate and outside deformation is more uniform.

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