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Springback behaviors of high strength stainless steel tube after numerical control rotary draw bending

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Abstract: Taking the 21-6-9 (0Cr21Ni6Mn9N) high strength stainless steel tube (HSSST) of 15.88 mm×0.84mm（diameter D×wall thickness t）as the objective, a three dimensional (3D) elastic plastic finite element（FE）model of the whole process of the 21-6-9 HSSST in numerical control (NC) rotary draw bending was established based on ABAQUS explicit/ implicit code, and its reliability was validated. Then, the effects of process parameters on springback of the 21-6-9 HSSST in NC rotary draw bending were studied using the FE simulation based on orthogonal test. The results show that the effects of process parameters on springback angle and radius form high to low are the clearance between tube and wiper die C_w, mandrel extension length e, clearance between tube and mandrel C_m, friction coefficient between tube and wiper die f_w, clearance between tube and pressure die C_p, friction coefficient between tube and bending die f_b, friction coefficient between tube and pressure die f_p, friction coefficient between tube and mandrel f_m, clearance between tube and bending die C_b, bending speed ω, push assistant speed of pressure die V_p and e, C_w, C_m, f_b, f_w, C_b, f_m, ω, C_p, f_p, V_p, respectively. Springback angle and radius decrease with the increase of C_w, e or decrease of C_m, f_b, f_w, f_m, C_b, while the C_p, f_b, V_p and ω have no obvious influence on springback.

1. Introduction

Owing to the unique characteristics of manufacturing lightweight and high strength bent-tube parts, tube bending is widely used in aerospace, aviation and other high technology industries [1]. Among various bending methods such as the compress bending, the stretch bending and the roll bending, the numerical control (NC) rotary draw bending is the most widely used method with the characteristics of high precision, high efficiency, low consumption and digitization. After the unloading of the tube NC rotary draw bending, the residual stress causes elastic deformation, which leads to the decrease of the bending angle and the increase of the bending radius. The springback greatly affects the shape and the dimensional accuracy of the bent-tube, and reduces the connection and sealing performance of tubes with other parts as well as the internal structure compact. 21-6-9 (0Cr21Ni6Mn9N) high strength stainless steel tube (HSSST) currently has been increasingly used in hydraulic, fuel, etc. systems for advanced aircraft and spacecraft due to high strength, corrosion resistance and oxidation resistance, which can satisfy the developing requirements of light weight, high strength and low consumption for products. However, due to the high ratio of the yield strength to elastic modulus of the 21-6-9 HSSST, the springback phenomenon is more significant than that of the aluminum alloy tube and common stainless steel tube. Therefore, in view of the increasingly strict requirements of aeronautics and astronautics fields for the size tolerance of the bent-tube parts, it is urgently needed to study the springback behaviors of the 21-6-9 HSSST in NC rotary draw bending, which can improve the prediction precision of the springback to develop the precision plastic forming theory and technology for the HSSST in NC rotary draw bending.

Up to now, many scholars have carried out a lot of researches on the springback of tube bending by using analytical, experimental and numerical approaches. Using the beam bending theory, Al-Qureshi et al.[2] derived the theoretical formulae of springback and residual stress distribution of the thin-walled aluminum alloy tube in pure bending based on the assumptions of ideal elastic plastic material, plane strain condition, absence of defects and Bauchinger effects. The formula of the springback angle was presented using the virtual work principle, and that of the springback radius was also given according to the length of the neutral layer remained unchanged before and after springback by Lu et al.[3]. Wu et al.[4] experimentally studied the effects of temperature, bending speed, original grain size and friction condition on the springback of tube rotary draw bending. The effects of forming parameters on the springback of thin-walled 6061-T4 aluminum alloy tubes in NC bending were researched by experiment in literature [5]. By finite element (FE) numerical simulation, Sözen et al.[6] discussed the springback phenomena of steel tube NC bending under the interactions between the geometrical and mechanical parameters and developed a surrogate model to predict fast the springback for a given combination of parameters. Using the plastic deformation theory, explicit/implicit FE simulation and experiment, the springback behaviors of the high strength Ti-3Al-2.5V titanium alloy tube NC bending were revealed, and a two level springback compensation method was presented to achieve the precision bending with respect to the springback angle and radius in Ref.[7,8]. In recent years, for the 21-6-9 HSSST bending and springback, Fang et al.[9-11] investigated the effects of friction conditions, geometrical parameters and material parameters on deformation or springback behaviors by using the theoretical analysis, FE simulation combined with the multi-parameter sensitivity analysis method and obtained the sensitivity of the springback to material parameters.

The most of the above researches focused on the springback of the aluminum alloy tube, steel tube and titanium tube bending, while the reports of the springback of the HSSST bending are still scant. Especially, the study on the effect of process parameters on the springback of the HSSST bending is little involved. Thus, in this work, taking the 21-6-9 HSSST as the objective, a three dimensional (3D) elastic plastic FE model of the whole process of tube NC rotary draw bending was established based on ABAQUS code, and its reliability was validated. Then, the effects of process parameters on the springback of tube bending and its significance were investigated using the FE simulation based on orthogonal test.

2. Explicit/implicit FE modeling and validation

Taking the 21-6-9 HSSST of 15.88 mm×0.84mm×47.64 mm（diameter D×wall thickness t×bending radius R）as the objective, a 3D elastic plastic FE model of the whole process of the 21-6-9 HSSST in NC rotary draw bending was established based on ABAQUS explicit/implicit code as shown in Figure 1. The model can consider the nonlinear dynamic contact conditions in rotary draw bending process and achieve the whole process simulation including bending tube, retracting mandrel and springback. The key technology solutions and forming parameters, such as process parameters, geometrical parameters and material parameters, of the modeling process are the same as the literatures [12].

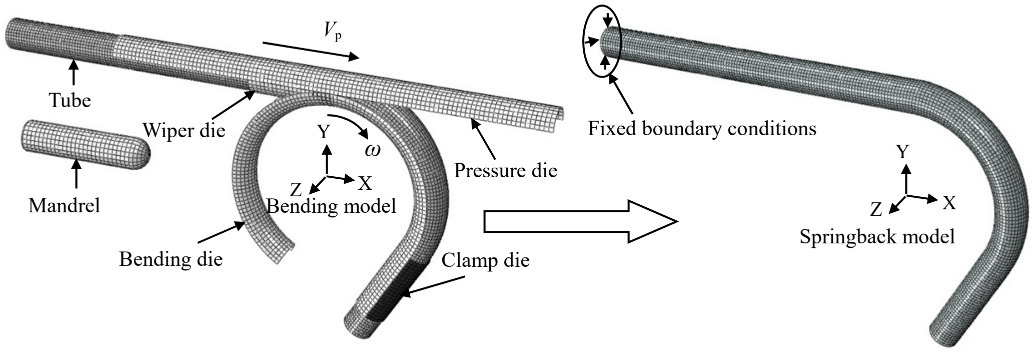

Figure 1. 3D elastic plastic FE model of whole process of 21-6-9 HSSST in NC rotary draw bending

In order to verify the reliability of the FE model, the experiments were carried out by the NC tube bender SB-12×3A-2S. The experimental conditions are as follows: the bent-tube specification for the 21-6-9 HSSST is 6.35 mm×0.41 mm×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 used to the contact interfaces.

Figure 2 shows the comparison between experimental and simulation results of the 21-6-9 HSSST in NC rotary draw bending. As can be seen form Figure 2 that the FE simulation results for springback angles agree with the experimental results. The maximum relative error is 15.55%, and the average relative error is 10.12%. Thus, the FE model is reliable, which can be used to study the springback behaviors of the 21-6-9 HSSST in NC rotary draw bending.

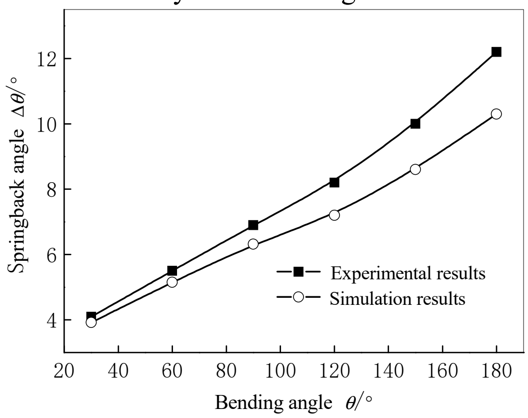

Figure 2. Comparison of results between experimental and simulation

3. Orthogonal test

The process parameters involved in the 21-6-9 HSSST NC rotary draw bending include the clearance between tube and mandrel C_m, clearance between tube and bending die C_b, clearance between tube and wiper die C_w, clearance between tube and pressure die C_p, friction coefficient between tube and mandrel f_m, friction coefficient between tube and bending die f_b, friction coefficient between tube and wiper die f_w, friction coefficient between tube and pressure die f_p, mandrel extension length e, push assistant speed of the pressure die V_p and bending speed ω. In order to study the effects of process parameters on the springback of the 21-6-9 HSSST in NC rotary draw bending, the above 11 process parameters were selected as the test factors, and three levels were selected for every test factor. The test factors and levels were listed in Table 1. The orthogonal array of $L_{27}(3^{13})$ was selected to carry out the tests according to the numbers of the factor and level. The virtual orthogonal test scheme could be seen in Ref.[13]. According to the test scheme, the whole process FE simulation of the 21-6-9 HSSST in NC rotary draw bending was carried out to obtain the springback angle $\Delta\theta$ and radius ΔR, and the values of these were listed in Table 2.

Table 1. Test factors and levels

Factors / Levels	C_m (mm)	C_b (mm)	C_p (mm)	C_w (mm)	f_m	f_b	f_p	f_w	e (mm)	V_p ($mm\cdot s^{-1}$)	ω ($rad\cdot s^{-1}$)
Level 1	0.05	0.10	0.10	0.05	0.05	0.10	0.10	0.05	2.00	17.15	0.4
Level 2	0.10	0.20	0.20	0.10	0.10	0.20	0.25	0.20	3.50	19.06	0.8
Level 3	0.20	0.25	0.30	0.20	0.15	0.30	0.40	0.30	5.00	20.96	1.2

4. Results and discussion

Table 3 shows the range analysis of the springback angle and radius, where $R_{\Delta\theta}$, $R_{\Delta R}$ are the range value of the springback angle and radius, respectively. It is found that the significance of process parameters on the springback angle of the 21-6-9 HSSST in NC rotary draw bending decreases in the order as C_w, e,C_m, f_w,C_p, f_b,f_p,f_m,C_b,ω and V_p, while the significance of process parameters on the springback radius from high to low is e, C_w, C_m,f_b,f_w, C_b,f_m, ω, C_p,f_p and V_p.

Figure 3 shows the relationship between factors (process parameters) and index (springback angle / radius). It can be seen from Figure 3 and Table 3 that the Cw, e and Cm have great influence on the springback of the 21-6-9 HSSST in NC rotary draw bending. Springback angle and radius decrease with the increase of the Cw and e, while the overall trend of the springback angle and radius increase with the increase of the Cm. These are because that, increasing the clearance between tube and wiper die Cw causes the possibility of tube wrinkling to increase. The onset of the wrinkling leads to materials accumulation, which makes the bending deformation force increase. Thus, the plastic deformation increases, and the corresponding elastic deformation decreases. Viz. springback angle and radius decrease. With the increase of the mandrel extension length e, the support role of the mandrel to tube increases, which causes the cross section distortion to decrease. Thus, the springback decreases after unloading. On the other hand, the deformation force of the tube NC rotary draw bending increases with the increase of the e, which makes the plastic deformation increase and corresponding elastic deformation decrease, namely, the ratio of plastic deformation to total deformation increases. Thus, the springback angle and radius decrease. These results are similar to the effect laws of the e on the springback of Al-alloy tube, high strength titanium tube in NC rotary draw bending [5,14]. With the increase of the clearance between tube and mandrel Cm, the friction force of the mandrel to tube decreases, namely, increasing the Cm facilitates tube bending deformation, thus the springback angle and radius increase with the increase of the Cm. These results are similar to the effect laws of the Cm on the springback of Al-alloy tube, high strength titanium tube in NC rotary draw bending [5,14].

Table 2. Test results of the springback angle and radius

Test	$\Delta\theta$ (°)	ΔR (mm)	Test	$\Delta\theta$ (°)	ΔR (mm)	Test	$\Delta\theta$ (°)	ΔR (mm)	Test	$\Delta\theta$ (°)	ΔR (mm)
1	8.456	1.783	8	8.340	1.877	15	5.220	1.170	22	9.068	1.978
2	8.014	2.062	9	8.547	1.801	16	9.310	2.257	23	9.669	2.441
3	8.180	1.893	10	6.970	1.321	17	7.882	1.571	24	8.970	2.000
4	8.030	1.691	11	7.924	1.770	18	9.739	2.319	25	9.664	2.265
5	7.227	1.348	12	7.940	1.638	19	7.621	1.849	26	7.046	1.804
6	9.569	2.135	13	8.065	1.874	20	8.167	1.719	27	8.171	1.859
7	6.665	1.293	14	7.107	1.503	21	7.505	1.869			

Table 3. Range analysis of the springback angle and radius

	C_m	C_b	C_w	C_p	f_m	f_b	f_w	f_p	e	V_p	ω
$R_{\Delta\theta}$	0.636	0.510	1.339	0.570	0.515	0.534	0.628	0.522	1.264	0.161	0.359

$R_{\Delta R}$	0.262	0.127	0.372	0.071	0.101	0.212	0.174	0.067	0.465	0.053	0.089

The fb, fw, fm and Cb have a certain influence on the springback of the 21-6-9 HSSST in NC rotary draw bending. The springback angle and radius increase with the increase of the fb, fw, fm and Cb, but the amplitude of variation is not obvious. These are because that, the friction force of the bending die to the inner side of bent-tube increases with the increase of the fb, namely, the tangential compression stress of the inner side of bent-tube increases, which causes the moment of the springback of bent-tube to increase. Thus, the springback angle and radius increase. This result is similar to that of the high strength titanium tube during NC rotary draw bending [14]. With the increase of the fw, the friction force of the wiper die to tube increases, which leads to the deformation of the inner side of bent-tube decrease. Viz., decreasing the plastic deformation and increasing elastic deformation. Therefore, the springback angle and radius increase with the increase of the fw. The axial tension force of tube bending increases and the bending moment decreases with the increase of the fm, which make the springback angle and radius decrease. Moreover, increasing the fm causes the tube and clamp die to easily slide, which leads to the wrinkling tendency of bent-tube increase. Thus, the springback increases significantly. The synthetic effects of the above make the springback angle and radius increase with the increase of the fm. Increasing the Cb makes the deformation degree decrease, namely, the bending stiffness decreases, which causes the springback angle and radius increase with the increasing of the Cb.

The Cp, fb, Vp and ω have less effects on the springback of the 21-6-9 HSSST in NC rotary draw bending. Thus, the subsequent optimized analysis can ignore the effect of these parameters.

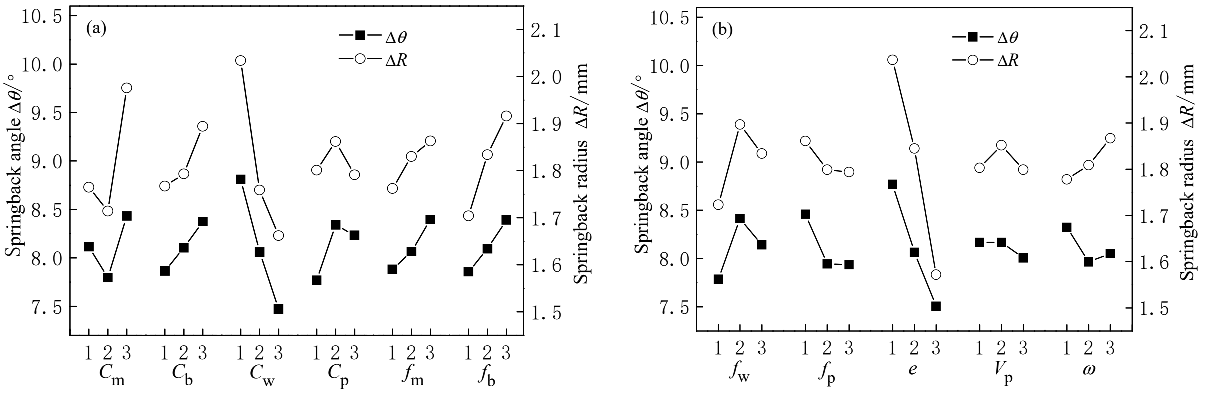

Figure 3. Relationship between factors (process parameters) and index (springback angle / radius)

5. Conclusions

(1) The significance of process parameters on the springback angle of the 21-6-9 HSSST in NC rotary draw bending decreases in the order as C_w, e,C_m, f_w,C_p, f_b,f_p,f_m,C_b, ω and V_p, while those on the springback radius from high to low is e, C_w, C_m,f_b,f_w, C_b,f_m, ω, C_p,f_p and V_p.

(2) The springback angle and radius of the 21-6-9 HSSST in NC rotary draw bending increase with the decrease of the C_w and e or increase of the C_m,f_b,f_w,f_m and C_b, while the C_p,f_b, V_p and ω have no obvious on the springback.

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