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Significance analysis of process parameters on cross section distortion of high-strength TA18 tube in numerical control bending

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Abstract: To achieve the precise numerical control (NC) bending and improve the forming quality of high-strength TA18 titanium alloy tube (TA18-HS tube), the significance of process parameters on cross section distortion in the TA18-HS tube NC bending should be clarified. Taking the TA18-HS tube of 6.35 mm×0. 4064mm (out diameter×wall thickness) as the objective, a three dimensional (3D) elastic plastic finite element (FE) model based on virtual orthogonal test was used to explore the effects of process parameters on cross section distortion behaviors in the TA18-HS tube NC bending. The results show that the clearance between tube and mandrel Cm, the clearance between tube and bending die Cb, the friction between tube and wiper die fw and the mandrel extension length e are significant factors for cross section distortion in the TA18-HS tube NC bending, and the significant factors on cross section distortion from high to low are the Cb, e, fw and Cm. The cross section distortion degree increases with the increase of the Cb , fw, Cm or with the decrease of the e.

1. Introduction

Due to low density, high strength, excellent corrosion resistance, high-pressure resistance, long life and good welding performance, high-strength TA18 titanium alloy tube (TA18-HS tube) has been increasingly used in the aerospace, aviation, and related high-technology industries as bleeding components. However, compared with stainless steel tube and aluminum alloy tube, the large deformation resistance and low elastic modulus of the TA18-HS tube cause various defects such as wall thinning, cross section distortion and springback, to produce easily during numerical control (NC) bending. The cross section distortion affects the strength of the bent-tube component and normal flow of the hydraulic medium inside the tube that directly affect the usability of the bent-tube. Among many factors that influence the cross section distortion in tube bending, process parameters play an important role to reduce the cross section distortion. Due to the interaction of process parameters in practical production process, the adjustment of process parameters is very difficult. Therefore, study on the influence significance of process parameters on cross section distortion of the TA18-HS tube in NC bending has an important theory significance and practical application value to improve forming quality and optimize process parameters.

Up to now, great efforts have been carried out on cross section distortion of tube bending by using analytical, experimental and numerical approaches. While most studies applied the single factor method to research the effects of the geometrical parameters, material parameters and process parameters on cross section distortion in tube bending. The influence significance of process parameters on cross section distortion in tube bending was less studied. Veerappand and Shanmugam[1] derived a calculation formula of the cross section distortion with assumptions of linear, uniform, isotropic material model, steady static loading and absence of “Bauschinger effect”. Liu et al.[2] presented a new method to calculate the cross section distortion based on the virtual principle of deformation system. Lu et al.[3] deduced a theoretical formula of the cross section distortion based on the plane strain assumption and exponent hardening law. The effect laws of process parameters on cross section deformation of aluminum alloy 3A21 thin-walled rectangular tube in rotary draw bending were experimentally obtained by Liu et al. [4]. Li et al.[5] experimentally studied the influence of process parameters on cross section distortion for large diameter thin-walled aluminum alloy tubes in NC bending process. Also by experimental analysis, the constraints of various dies on cross section distortion of 3A21 rectangular tube in rotary draw bending were studied in Ref.[6]. By finite element (FE) analysis, Fang et al.[7-9] investigated the effects of the geometrical parameters, push assistant speed and material parameters on cross section distortion of the TA18-HS tube in NC bending. In literature [10], an elastic plastic FE model of 21-6-9 stainless steel tube in NC bending was established, and the effect laws of friction conditions on cross section distortion were revealed.

Therefore, In the paper, Taking the TA18-HS tube of 6.35 mm×0. 4064mm (out diameter×wall thickness) as the objective, a three dimensional (3D) elastic plastic FE model of the TA18-HS tube in NC bending is established under the platform of ABAQUS combined with virtual orthogonal test. Then, the influence significance and law of process parameters on cross section distortion of the TA18-HS tube in NC bending are obtained.

2. FE model establishment and validation

According to the practical tube NC bending process, an explicit/implicit 3D elastic plastic FE model of the whole process of the TA18-HS tube in NC bending was established under the platform of ABAQUS as shown in Figure 1. The explicit algorithm was applied to tube bending and mandrel retracting operations, while the implicit one was employed for unloading springback operation. The mechanical properties of the TA18-HS tube was gained by uniaxial tension test in Ref.[11]. For unloading springback operation, all dies were removed, and a fixed boundary condition was used to avoid the rigid motion. The detailed modeling process can be found in Ref.[7].

For post-processing, the cross section distortion degree of the bent tube was calculated after the springback simulation finished because the springback may have obvious effect on cross section distortion.

In order to validate the reliability of the FE model, the TA18-HS tube with the specification of 9.525 mm×0.508 mm was carried out by FE simulation under the bending conditions in Ref.[12].

Figure 2 shows the comparison between FE simulation and experiment results obtained in Ref.[12]. It is found that the FE simulation results for the cross section distortion degree ΔD [7] agree with the experimental ones with the maximum relative error of 13.8%. Therefore, the FE model is credible, which can be used to explore the influence significance and law of process parameters on cross section distortion of the TA18-HS tube in NC bending.

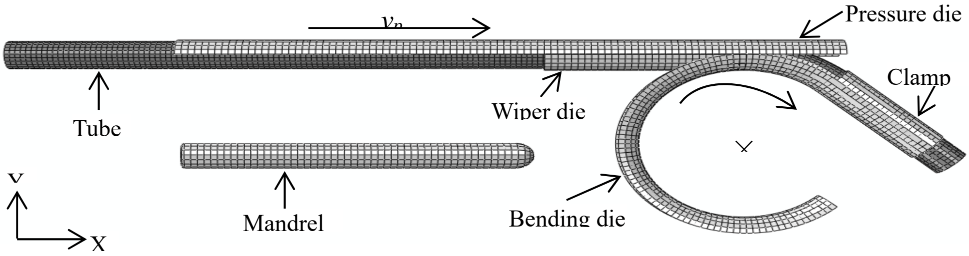

Figure 1. 3D elastic plastic FE model for TA18-HS tube in NC bending

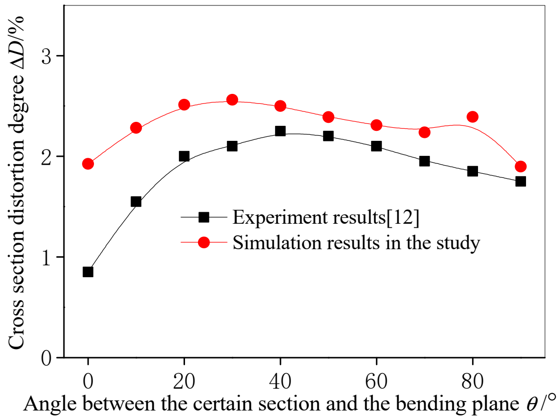

Figure 2. Comparison of simulation results with experimental results

3. Orthogonal test

The process parameters of the TA18-HS tube in NC bending include the clearance/friction between tube and mandrel Cm/fm, the clearance/friction between tube and bending die Cb/fb, the clearance/friction between tube and pressure die Cp/fp, the clearance/friction between tube and wiper die Cw/fw, the mandrel extension length e, the push assistant speed of pressure die vp and the bending speed ω. Table 1 shows the levels of process parameters. According to the Table 1, the orthogonal array L27(313) was selected to conduct test. The test scheme could be found in literature [13]. The maximum cross section distortion degree ΔDmax with bending angle 180° was obtained by FE simulation in accordance with the scheme, and the results were listed in Table 2. During FE simulation process, the slide between clamp die and tube did not happen, and the defects including wrinkling and crack also were not discovered.

Table 1. Levels of process parameters

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	ω (rad·s^{-1})
Level 1	0.075	0.1	0.1	0.1	0.05	0.1	0.15	0.1	0	0.8	0.4
Level 2	0.150	0.2	0.2	0.2	0.15	0.2	0.25	0.2	1	1.0	0.8
Level 3	0.225	0.3	0.3	0.3	0.25	0.3	0.35	0.3	2	1.2	1.2

4. Results and discussion

The method of variance analysis was used to study the significance of process parameters on cross section distortion in tube bending. The critical values F1-α(fF, fE) of the significance level α with 0.01, 0.05 and 0.1 were obtained by F distribution table. Where fF and fE are freedom degree of factor and error, respectively. Compared the F-value of various factors with the critical value, if F⩾F1-0.01(fF, fE), then this influence factor is highly significant, and the mark of " * * " is applied; if F1-0.01(fF, fE)＞F⩾F1-0.05(fF, fE), then this influence factor is significant, and the mark of " * " is employed; if F1-0.05(fF, fE)＞F⩾F1-0.1(fF, fE), then this influence factor has a little significant, and the mark of " (*)" is used; if F＜F1-0.1(fF, fE), then this influence factor is not significant[13].

Table 2. Test results of maximum cross section distortion degree ΔDmax

Test	ΔD_{max}(%)	Test	ΔD_{max}(%)	Test	ΔD_{max}(%)	Test	ΔD_{max}(%)
1	4.407	8	7.057	15	5.603	22	7.471

2	3.499	9	5.407	16	11.501	23	6.478
3	5.246	10	4.773	17	5.896	24	4.1
4	4.19	11	4.076	18	4.589	25	8.074
5	4.177	12	6.67	19	5.348	26	7.552
6	5.737	13	4.067	20	8.181	27	9.739
7	11.09	14	6.874	21	6.95		

Table 3 shows the results of variance analysis for cross section distortion. It can be seen from the Table 3 that, Cb, fw and e are the highly significant factors on cross section distortion in tube bending; Cm is a significant factor on cross section distortion and the others have little effect on cross section distortion. The significant factors on cross section distortion from high to low are Cb, e, fw and Cm.

Figure 3 shows the effect of significant process parameters on the maximum cross section distortion degree. As can be seen from that the maximum cross section distortion degree increases with the increase of the Cb , fw, Cm or with the decrease of the e. The reasons are that, the tangential friction force between bending die and tube can counteract a part of acting force, which causes the cross section distortion. With the increase of the Cb, the tangential friction force of bending die to tube becomes smaller and smaller, thus the cross section distortion increases. The larger fw causes the tangential tensile stress to increase, which leads to the increase of the cross section distortion. The support role of mandrel to tube decreases with the increase of the Cm, which makes the cross section distortion increase. With the decrease of the e, the support role of mandrel to tube decreases. Therefore, the cross section distortion increases with the decrease of the e.

Table 3. Variance analysis for cross section distortion

Process parameters	Sum of squares	Freedom degree	Mean square variance	F-value	Significance
C_m	10.317	2	5.159	5.220	*
C_b	35.803	2	17.902	18.114	* *
C_p	3.300	2	1.650	1.670	
C_w	0.253	2	0.127	0.128	
f_m	3.639	2	1.820	1.841	
f_b	1.217	2	0.609	0.616	
f_p	2.505	2	1.253	1.267	
f_w	19.505	2	9.753	9.868	* *
e	21.630	2	10.815	10.944	* *
v_p	6.615	2	3.308	3.347	(*)
ω	5.854	2	2.927	2.962	(*)
Error	7.91	8	0.989		
$F_{1-0.01}(2,8)=8.65$, $F_{1-0.05}(2,8)=4.46$, $F_{1-0.10}(2,8)=3.11$					

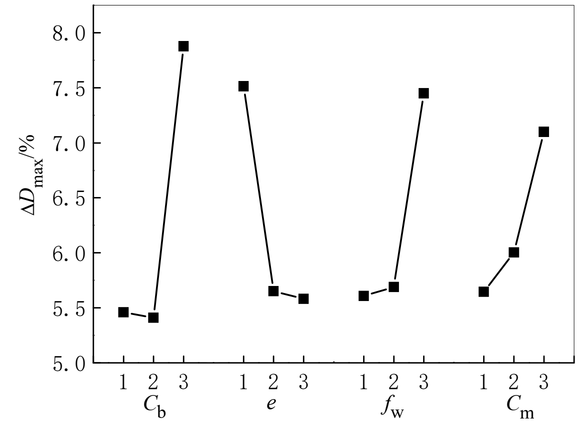

Figure 3. Effect of significant process parameters on ΔDmax

5. Conclusions

(1) The clearance between tube and mandrel Cm, the clearance between tube and bending die Cb, the friction between tube and wiper die fw and the mandrel extension length e are significant factors for cross section distortion in the TA18-HS tube NC bending and the others have little effect on cross section distortion.

(2) The significant factors on cross section distortion in the TA18-HS tube NC bending from high to low are the Cb, e, fw and Cm.

(3) The cross section distortion degree increases with the increase of the Cb , fw, Cm or with the decrease of the e.

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