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Significant analysis of the influence of process parameters on the wrinkling of aluminum alloy double-wall gap tube in rotary draw bending

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Abstract. Aluminum alloy double-wall gap tube is prone to wrinke in the rotary draw bending because the rigidity of the inner and outer tubes of the thin-walled structure is low, the mechanical properties between the tubes and the polymer filling medium are different greatly, and the bending forming is a complex nonlinear process of multi-mold coordination and multi-factor coupling. While the process parameters are the main factors that affect the wrinkling of inner and outer tube, there are many process parameters and there are interactions among them. Therefore, based on the platform of ABAQUS/Explicit, elastic-plastic 3D-FE model of double-wall gap tube's bending is established to study the influence mechanism of process parameters on the wrinkling aluminum alloy double-wall gap tube in rotary draw bending. The results show that the clearance between mandrel and inner tube, clearance between pressure die and outer tube, the anti-wrinkle die and the outer tube have significant effects on the wrinkling of the inner tube. The clearance between inner tube and core die, filling medium and inner tube and clearance between anti-wrinkle die and outer tube have significant effects on the wrinkling of inner tube. The wrinkling of the outer tube is more obvious than that of the inner tube. The results can provide a theoretical basis for optimizing the process parameters to suppress the wrinkling of aluminum alloy double-wall gap tube in the rotary-draw bending.

1. Introduction

Aluminum alloy double-wall gap tube is expected to meet the requirements of lightweight, long life, heat insulation and leakage prevention of advanced aerospace equipment pipeline system due to the use of 6061-T4 aluminum alloy with high specific strength and a unique double-wall gap structure. In order to ensure that the forming force can be transferred between the inner and outer tubes, and at the same time retain the double-wall structure of aluminum alloy double-wall gap tube before and after forming, it is considered to add polymer filling medium between the inner and outer tubes to assist the inner and outer tube bending forming. However, the rigidity of the inner and outer tubes of the thin-walled structure is low, the mechanical properties of the inner and outer tubes and the polymer filling medium are different greatly, and the digital-controlled bending forming is a complex nonlinear process of multi-die coordination and multi-factor coupling, which is easy to produce wrinkle, severely restricts the double-wall gap tube forming quality. Among many influencing factors, process parameters play an important role, and reasonable selection of process parameters can effectively improve the forming quality.

At present, there are few papers on the bending forming of double tubes at home and abroad. Pasqualino and Lourenco et al [1-2] studied the influence of adhesion degree between filling medium and inner and outer tubes and material properties on buckling instability of double-layer tubes during bending through experiments and finite element simulation, but this study has not taken into account the effect of process parameters on wrinkling. Sun et al [3] used 3D-FEM to study the different filling materials on double-wall gap tube wrinkling behavior and found that using the filling medium PMMA and PVC have obvious inhibitory effect on wrinkling. However, there are many papers on defects of single tube bending at home and abroad. Cheng et al[4] studied the influence of the core position, the mandrel core count and the clearance between mandrel and the tube on the free bending quality of thin-walled tube.Fang et al[5] studied the influence of bending angle, relative bending radius and tube sizes on forming quality of high-strength TA18 round tubes by using finite element simulation and found that the wall thickness change rate and section distortion rate decrease with the increase of the relative bending radius, and increase with the increase of the bending radius and wall thickness. Zhang et al[6] studied the influence of pressure die parameters on the forming quality of large-diameter thin-walled metal circular tube in bending by finite element simulation, and found that increasing pressure die pressure could effectively reduce the reduction of wall thickness and axial elongation of the tube. Li [7] studied wrinkling behavior in tube compression test and bending forming test through finite element simulation, and found that in the process of bending forming with normal constraints, ripple instability was effectively reduced. Although in the above articles, some pipe structures or bending forms are different from those of double-wall gap pipes, some do not systematically consider the influence of process parameters on forming quality, these papers provide reference for the study of double – wall gap tube bending forming process. There are many and complex process parameters affecting the wrinkling of aluminum alloy double-wall gap tube bending forming, and there is mutual coupling between the factors, so it is time-consuming, difficult and inefficient to conduct a comprehensive study. Therefore, based on our existing FEM of the NC-bending forming of aluminum alloy thin-walled tube under multi-die constraints [9-10], the 3D-FEM of aluminum alloy double-wall gap tube bending was established and the significant effect of process parameters on wrinkling was simulated by using virtual orthogonal experiment.

2. Finite element model

2.1. The establishment of finite element model

After geometric model establishment, model assembly, contact condition processing, mesh division and other steps, the three-dimensional bending forming finite element model of aluminum alloy double-wall gap tube was established, as shown in figure 1.

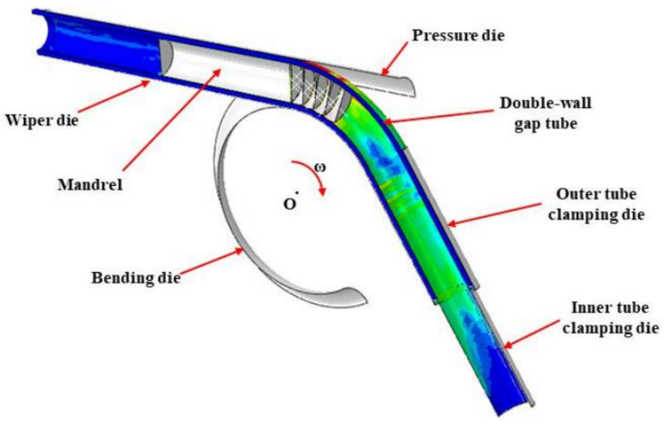

Figure 1. The finite element model of 6061-T4 aluminum alloy double-wall gap tube bending forming.

2.2. Description of corrugation

It is necessary to describe the corrugation ripple quantitatively during studying the effect of process parameters on the instability wrinkling of double-wall gap tube. A preliminary study on wrinkling in bending forming of aluminum alloy double-wall gap tube shows that the parts causing instability wrinkling include bending forming section (AB) and bending end straight section (BC), as shown in figure 2.

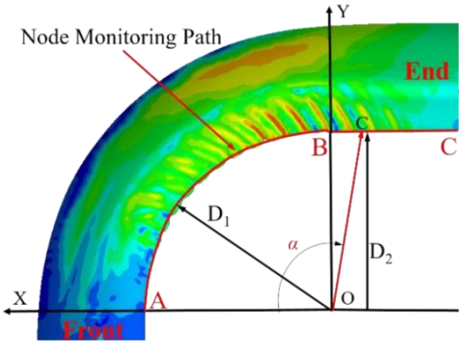

Figure 2. Schematic diagram of corrugation ripple in double - wall gap tube bending.

A measurement path was established on the inner ridge line of the tube to obtain the corrugate wave distance *D*, and α in the figure is the Angle from the measurement path to the initial bending section. For AB segment, the corrugation fluctuation distance *D* is the distance between each node of the inner ridge line and the rotation center. For BC segment, the value of *D* is the distance from the node on the inner ridge to the initial bending section, as shown in the following equation (1).

$$D = \begin{cases} \sqrt{x^2 + y^2} & (\alpha \le 90^\circ) \\ y & (\alpha > 90^\circ) \end{cases} \tag{1}$$

In this paper, the size of corrugations is described by defining W , ΔH is the difference of corrugations distance D between adjacent peaks and troughs, and the maximum value of ΔH is W , the calculation formula of W is shown as equation (2).

$$W = \max\{\Delta h\} = \max\{D_i - D_j\} \tag{2}$$

2.3. Validation of model accuracy

In order to verify the accuracy of the simulation results of the finite element model established above, numerical control bending experiments with the same pipe specifications, die constraints, material types and forming parameters of the model established were carried out and compared with the simulation results. The basic mechanical properties of aluminum alloy thin-walled tube used in the experiment are shown in table 1. The bending experiment was carried out on W27YPC-63 CNC pipe bender. The die and bending equipment are shown in figure 3(a) and (b) respectively. First install the die properly on the device, ensure close contact between dies, then make the aluminum alloy double-walled tube rotating-bending experiment according to the finite element model's parameters, specific parameters are shown in table 2, in addition to the parameters shown in table 2, the rest of the mould tube billet close contact with the inner and outer tubes, there are no clearance.

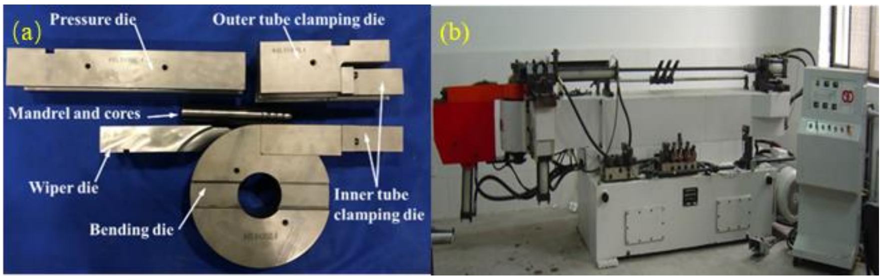

Figure 3. Bending forming experiment of double-wall gap tube:(a) Bending die;(b) W27YPC-63 CNC pipe bender.

Table 1. Basic mechanical properties of 6061-T4 aluminum alloy pipe.

Different specifications / Material parameters	Φ31.75×t0.7mm	Φ44.45×t0.7mm
Modulus of elasticity E(GPa)	59.10	59.93
Poisson's ratio ν	0.33	0.33
Initial yield stress σ_0 (MPa)	176.8	167.1
Hardening index n	0.270	0.275
Coefficient of strength K (MPa)	537.02	517.51
Thick anisotropy index γ_0	0.808	0.626

Table 2. Experimental conditions and finite element model simulation conditions of the bending process.

Parameter	simulation	Experiment
Bending Angle (°)	90	90
Bending speed (rad /s)	0.8	0.8
Bending radius (mm)	95.25	95.25
Boost matching (%)	100%	100%
Clearance between inner tube and core die (mm)	0.1	0.1
Clearance between inner tube and filling medium (mm)	0.16	0.16
Clearance between outer pipe and filling medium (mm)	0.22	0.22
Clearance between outer tube and anti-wrinkle die (mm)	0.2	0.2
Clearance between inner/ outer tubes and other dies (mm)	0	0
Coefficient of friction between inner and outer tube and clamping die	rough	Dry friction
Coefficient of friction between inner and outer tube and filling medium	0.15	Small amount of aviation lubricating oil
Coefficient of friction between inner and outer tubes and other dies	0.1	Some aviation lubricating oil

Figure 4(a) and (b) respectively show the inner tube results obtained by finite element simulation and bending forming test under the above conditions. As can be seen from the figure 4, both of them have no obvious forming defects.

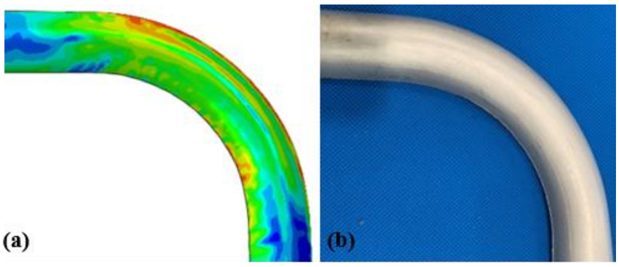

Figure 4. Bending forming of aluminum alloy double-wall gap tube: (a) Simulation results;(b) Experiment results.

Figure 5 is the simulation and experiment results of outer tube bending forming of double-wall gap tube obtained under the above conditions. It can be seen that the similar distribution pattern of corrugation appears in both simulation and experiment results, and the number of corrugation were both 15. In order to quantitatively verify the accuracy of the model, the distribution rule of the corrugation ripple of the outer tube was obtained through experiments and simulations, as shown in figure 6. The corrugations of the simulated and experimental results are in the range of α=15~115°. The maximum difference of corrugations between the simulated and experimental results is about α=85°, but the maximum difference is less than 22%, and the error of corrugations spacing is less than 5%. Therefore, the finite element model established in this paper is accurate.

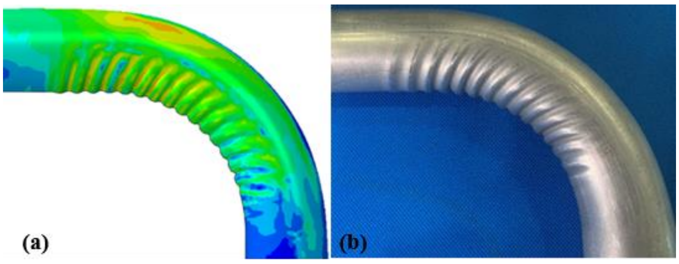

Figure 5. Bending of outer tube of aluminum alloy double-wall gap tube:(a) Simulation results;(b) Experiment results.

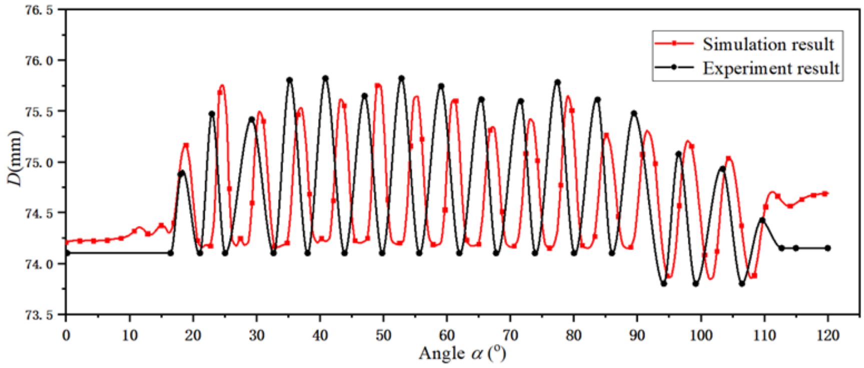

Figure 6. Distribution of corrugation in outer tube obtained by experiment and simulation.

3. Design of process parameters affecting wrinkling

For aluminum alloy double-wall gap pipe with a certain cross-section size, soft and tough PTFE was selected as the filling medium, and the material properties of PTFE were defined by DSGZ constitutive model established by Vumat subroutine. Some parameters related to the bending process of aluminum alloy double - wall gap tube were selected: the core number N, mandrel extension e_m ,clearance between mandrel and inner tube δ_m, clearance between pressure die and outer tube δ_p, clearance between anti-wrinkle die and outer tube δ_w, clearance between bending die and outer tube δ_b, bending radius R_0, the gap between inner and outer tube and filling medium δ_f, and the friction coefficient between filling medium and inner and outer tube μ_f. Three levels of each factor are selected from reasonable ranges of variation for these process parameters, show as table 3. The L_{27} (3^{13}) orthogonal table at 13 factor 3 level was selected to arrange the virtual orthogonal test, as shown in Table 4, and the remaining process parameters in the model remained unchanged. The degree of corrugation of inner and outer tubes W are taken as test indexes. The simulation results are shown in the last two column of table 4.

Table 3. There levels distribution of factors.

Factors	Level 1	Level 2	Level 3
Core number N	3	4	5
Mandrel extension e_m (mm)	3.2	4	4.8
Clearance between mandrel and inner tube δ_m (mm)	0.1	0.2	0.3
Clearance between pressure die and outer tube δ_p (mm)	0	0.1	0.2
Clearance between anti-wrinkle die and outer tube δ_w (mm)	0	0.1	0.2
Clearance between bending die and outer tube δ_b (mm)	0	0.1	0.2
Bending radius R_0 (nD)	2.5D	3D	3.5D
The gap between inner and outer tube and filling medium δ_f (mm)	0	0.1	0.2
The friction coefficient between filling medium and inner and outer tube μ_f	0.02	0.08	0.15

Table 4. Virtual orthogonal test arrangements and results.

Test serial number	1	2	3	4	5	6	7	8	9	10	11	12	13	W ($\times 10^{-2}$mm)	
	N	e_m	δ_m	δ_p	δ_w	δ_b	R_0	δ_f	μ_f					Inner tube	Outer tube
1	1	1	1	1	1	1	1	1	1	1	1	1	1	87.17	60.91
2	1	1	1	1	2	2	2	2	2	2	2	2	2	99.33	165.8
3	1	1	1	1	3	3	3	3	3	3	3	3	3	109.8	190.0
4	1	2	2	2	1	1	1	2	2	2	3	3	3	83.98	204.7
5	1	2	2	2	2	2	2	3	3	3	1	1	1	110.6	204.6
6	1	2	2	2	3	3	3	1	1	1	2	2	2	162.0	208.4
7	1	3	3	3	1	1	1	3	3	3	2	2	2	97.33	208.5
8	1	3	3	3	2	2	2	1	1	1	3	3	3	95.00	200.7
9	1	3	3	3	3	3	3	2	2	2	1	1	1	116.5	195.7
10	2	1	2	3	1	2	3	1	2	3	1	2	3	44.99	34.01
11	2	1	2	3	2	3	1	2	3	1	2	3	1	93.77	190.0
12	2	1	2	3	3	1	2	3	1	2	3	1	2	108.3	199.6
13	2	2	3	1	1	2	3	2	3	1	3	1	2	113.3	198.4
14	2	2	3	1	2	3	1	3	1	2	1	2	3	162.1	247.6
15	2	2	3	1	3	1	2	1	2	3	2	3	1	144.0	182.9
16	2	3	1	2	1	2	3	3	1	2	2	3	1	118.0	189.1
17	2	3	1	2	2	3	1	1	2	3	3	1	2	68.85	156.4
18	2	3	1	2	3	1	2	2	3	1	1	2	3	84.64	177.9
19	3	1	3	2	1	3	2	1	3	2	1	3	2	78.92	152.6

Test serial number	1	2	3	4	5	6	7	8	9	10	11	12	13	W ($\times10^{-2}$ mm)	
	N	e_m	δ_m	δ_p	δ_w	δ_b	R_0	δ_f	μ_f					Inner tube	Outer tube
20	3	1	3	2	2	1	3	2	1	3	2	1	3	118.0	155.6
21	3	1	3	2	3	2	1	3	2	1	3	2	1	102.0	230.1
22	3	2	1	3	1	3	2	2	1	3	3	2	1	21.81	81.05
23	3	2	1	3	2	1	3	3	2	1	1	3	2	80.04	172.7
24	3	2	1	3	3	2	1	1	3	2	2	1	3	85.37	179.0
25	3	3	2	1	1	3	2	3	2	1	2	1	3	81.24	218.1
26	3	3	2	1	2	1	3	1	3	2	3	2	1	127.0	158.5
27	3	3	2	1	3	2	1	2	1	3	1	3	2	108.0	216.5

4. Results and discussion

4.1. Range analysis of virtual orthogonal test results (inner tube)

Range analysis was conducted on corrugation degree W of inner tube in the virtual orthogonal test above, and the results are shown in table 5.

Table 5. Range analysis table for wrinkling corrugation degree W of inner tube in L_{27}（3^{13}）orthogonal test.

Factos	$\bar{K}_{i1}$	$\bar{K}_{i2}$	$\bar{K}_{i3}$	K
N	106.86	104.22	89.153	17.707
e_m	93.587	107.02	99.618	13.433
δ_m	83.890	102.21	114.13	30.24
δ_p	114.66	103.00	114.13	11.66
δ_w	80.749	106.08	113.04	32.291
δ_b	103.38	97.399	99.443	5.981
R_0	98.730	91.538	109.96	18.422
δ_f	99.256	93.259	107.71	14.451
μ_f	108.93	91.214	100.08	17.716

According to the range of the influencing factors in table 5, it can be seen that the primary and secondary order of the influence of each process parameter on the corrugation degree W of the inner tube is: (δ_w)>(δ_m)>(R_0)>(μ_f)>(N)>(δ_f)>(e_m)>(δ_p)>(δ_b). Based on the inner tube corrugation degree W as small as possible principle, according to table 5, the optimal level combination of each process parameter is $1_3 2_1 3_1 4_3 5_1 6_2 7_2 8_2 9_2$($N$=5, e_m =3.2mm, δ_m =0.1mm, δ_p =0.2mm, δ_w =0mm, δ_b = 0.1mm, R_0=3D, δ_f =0.1mm, μ_f =0.05). This parameter combination did not appear in the arranged 27 tests, and the corrugation degree W of this combination was simulated to be 0.2056 mm, which was the best among all tests.

4.2. Variance analysis of virtual orthogonal test results (inner tube)

Variance analysis method was used to carry out significant analysis on the technological parameters affecting the inner tube bending forming process, and the results were shown in table 6. It can be seen that among the selected process parameters, the influence of δ_m, δ_p, δ_w is significant, while the influence of other factors is not significant.

Table 6. Variance analysis table for wrinkling corrugation degree *W* of inner tube in L_{27}（3^{13}）orthogonal test.

Source of variance	Sum of squares of deviations	Degree of freedom	Standard deviation	*F*	Critical value	Significance
N	1641.84	2	820.92	1.680	$F_{0.01}(2,8)$	-
e_m	815.143	2	407.5715	0.8342	$=8.65$	-
δ_m	4175.89	2	2087.945	4.273		*
δ_p	4149.96	2	2074.98	4.247	$F_{0.5}(2,8)$	*
δ_w	5283.93	2	2641.965	5.407	$=4.46$	**
δ_b	166.617	2	83.3085	0.1705		-
R_0	1551.46	2	775.73	1.588	$F_{0.1}(2,8)$	-
δ_f	949.122	2	474.561	0.9713	$=3.11$	-
μ_f	1412.46	2	706.23	1.445		-
error	3908.67	8	488.58375			
summation	24055.1	26				

4.3. Range analysis of virtual orthogonal test results (outer tube)

Range analysis was conducted on corrugation degree *W* of outer tube in the virtual orthogonal test above, and the results are shown in table 7.

Table 7. Range analysis table for wrinkling corrugation degree *W* of outer tube in $L_{27}(3^{13})$ orthogonal test.

Factos	$\bar{K}_{i1}$	$\bar{K}_{i2}$	$\bar{K}_{i3}$	K
N	182.15	175.10	173.79	8.36
e_m	153.18	186.59	191.27	38.09
δ_m	152.54	181.60	196.90	44.36
δ_p	182.08	186.60	162.36	24.24
δ_w	149.71	183.54	197.79	48.08
δ_b	169.03	179.80	182.21	13.18
R_0	188.19	175.92	166.93	21.26
δ_f	148.15	176.18	206.70	58.55
μ_f	173.27	173.38	184.39	11.12

According to the range of the influencing factors in table 7, it can be seen that the primary and secondary order of the influence of each process parameter on the corrugation degree *W* of the outer tube is:(δ_f)>(δ_w)>(δ_m)>(e_m)>(δ_p)>(R_0)>(δ_b)>(μ_f)>(N).Based on the outer tube corrugation degree *W* as small as possible principle, according to table 7, the optimal level combination of each process parameter is $1_3 2_1 3_1 4_3 5_1 6_1 7_3 8_1 9_1$($N$=5, e_m =0.1mm, δ_m =0.1mm, δ_p =0.2mm, δ_w =0mm, δ_b =0mm, R_0=3.5D, δ_f =0mm, μ_f =0.02). This parameter combination did not appear in the arranged 27 tests, and the corrugation degree *W* of this combination was simulated to be 0.3143 mm, which was the best among all tests.

4.4. Variance analysis of virtual orthogonal test results (outer tube)

Variance analysis method was used to carry out significant analysis on the technological parameters affecting the outer tube bending forming process, and the results were shown in table 8. It can be seen that among the selected process parameters, the influence of δ_f, δ_w, δ_m is significant, while the influence of other factors is not significant.

Table 8. Variance analysis table for wrinkling corrugation degree *W* of outer tube in L_{27} (3^{13}) orthogonal test.

Source of variance	Sum of squares of deviations	Degree of freedom	Standard deviation	*F*	Critical value	Significance
N	363.218	2	181.609	0.1240	$F_{0.01}(2,8)$	-
e_m	7766.85	2	3883.425	2.651	$=8.65$	-
δ_m	9139.24	2	4569.62	3.119		*
δ_p	2989.97	2	1494.985	1.021	$F_{0.5}(2,8)$	-
δ_w	10978.9	2	5489.45	3.747	$=4.46$	*
δ_b	885.540	2	442.77	0.3023		-
R_0	2049.34	2	1024.67	0.6995	$F_{0.1}(2,8)$	-
δ_f	15431.7	2	7715.85	5.267	$=3.11$	**
μ_f	734.360	2	367.18	0.2507		-
error	11718.98	8	1464.8725			
summation	62058.1	26				

4.5. Comparative analysis of test results

As can be seen from table 5 and table 6, the process parameters that have significant influence on wrinkling of inner tube are δ_w, δ_p, δ_w; As can be seen from table 7 and table 8, the process parameters that have significant influence on wrinkling of outer tube are δ_f, δ_w, δ_m. These parameters are the main factors affecting the wrinkling of inner and outer tube of aluminum alloy double-wall gap tube. When the influence of process parameters on the wrinkling of double-wall gap tube bending forming under multi-die constraints was studied, these process parameters can be considered emphatically. In addition, under the same test conditions, the number, degree and scope of corrugation of the outer tube are greater than that of the inner tube, the wrinkling phenomenon is more obvious. These results greatly simplify the analysis of the influence of process parameters on wrinkling in the process of double-wall gap tube forming, which can lay a foundation for debugging the die and making the forming process in the actual production.

5. Conclusion

- A three-dimensional finite element model of aluminum alloy double-wall gap tube bending process was established, and its reliability was verified by experiments.
- The primary and secondary order of the influence of process parameters on inner tube wrinkling is (δ_w)>(δ_m)>(R_0)>(μ_f)>(N)>(δ_f)>(e_m)>(δ_p)>(δ_b), and the parameters that have significant influence on the instability and wrinkling of the inner tube are δ_m, δ_p, δ_w.
- The primary and secondary order of the influence of process parameters on outer tube wrinkling is (δ_f)>(δ_w)>(δ_m)>(e_m)>(δ_p)>(R_0)>(δ_b)>(μ_f)>(N), and the parameters that have significant influence on the instability and wrinkling of the inner tube are δ_f, δ_w, δ_m.
- The wrinkling of the outer tube is more obvious than that of the inner tube during bending forming.

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