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Hydroforming simulation and analysis of Ω-shape expansion joint

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Abstract. In this paper, the finite element simulation software ANSYS Workbench Transient Structural module was employed to simulate the hydroforming process of a three-layer three-wave Ω-shape bellows. The stress and strain fields, the wall thickness thinning rate at the peak and the roundness of each layer after hydroforming of the Ω-shaped bellows were analyzed. Results show that the maximum equivalent stress of von Mises before unloading is mainly distributed on the large arc. But after unloading, the maximum equivalent stress of von Mises is mainly distributed at the transition between the large arc and small arc with the maximum stress being about 33.15% lower than that before unloading.The maximum value of the equivalent total strain of von Mises before and after unloading is always near the maximum displacement of the bellows along the direction of wave height with the maximum being about 0.2.The elastic springback in the direction of wave height after hydroforming is about 1.70mm. The wall thickness thinning rate at the peak of the three-layer three-wave Ω-shape bellows is as large as 14 %.

1. Introduction

Theoretical calculations and experimental tests are two methods for studying bellows, and theoretical calculations include analytical methods, numerical methods, and engineering approximations. Before the 1970s, the analytical method was mainly used. However, since the 1970s, with the rapid development of computer technology, the finite element method has been accepted by more and more researchers with its unique advantages in solving geometric nonlinearities, material nonlinearities and boundary nonlinearities [1]. Y Liu, H Xu *et al.* applied the finite element method to numerically simulate and analyze the expansion joints. By comparing the finite element calculation with the standard calculation, it was found that the finite element calculation value is very similar to the standard calculation value, which indicates that the finite element method is reliable and feasible used for the bellows expansion joint analysis [2]. H Sun *et al.* carried out the strength design of the bellows and numerical simulation of hydroforming. They compared the numerical simulation results with the actual hydraulic forming results of the factory. The results show that the deviation of wave pitch, wave height, bellows bus length and peak thickness is less than 5%, which also shows that the simulation of finite element on bellows hydroforming is credible [3]. J Liu *et al.* established the finite element models of single and double layer U-shaped stainless steel bellows and compared them with experimentally obtained bellows to verify the correctness of the models. It is concluded that the thickness thinning rate of single-layer bellows is greater than that of double-layer bellows. For the double-layer bellows, the thickness thinning rate of the inner layer is greater than that of the outer layer. And the dimensional change of the double-layer bellows after springback is larger than that of the single-layer bellows. Using the same method, they simulated the hydraulic bulging process of the multi-layer bellows, and studied the effect of the number of layers on the wall thickness and wave height of the bellows. It is found that: at the peaks of the crests and troughs, the thinning rate of the outer layer is the largest; in the corrugated straight wall area, the thinning rate of the inner layer is the largest; when the total thickness is the same, the more the number of layers, the larger the wave height of the bellows; the increase of the number of layers of the bellows can reduce the tendency of the peak to break [4,5]. M S Ye *et al.* performed finite element numerical simulation on the hydroforming process of two-layer four-wave Ω-shaped bellows. They investigated the stress field distribution and structural parameter changes in the bellows before and after forming. Also they studied the factors affecting the roundness and thickness thinning amount of the bellows after forming. Their simulation results were verified through experiments [6].

In this paper, the finite element simulation software ANSYS Workbench will be used to simulate the hydroforming process of a three-layer three-wave Ω-shaped bellows expansion joint. Stress and strain fields, wall thickness thinning rate at the peak and the roundness of the Ω-shaped bellows after hydroforming will be analyzed.

2. Hydroforming simulation of Ω-shaped bellows

2.1. Geometric model and mesh model

The hydroforming process of bellows involves geometric nonlinearity, material nonlinearity, and nonlinear contact state. Therefore, the Transient Structural module is used to simulate the hydroforming process of the bellows. Since the bellows and the mold shape are both axisymmetric and the force is also symmetrical, a 2D axisymmetric model can be established instead of the 3D model to shorten the calculation time.

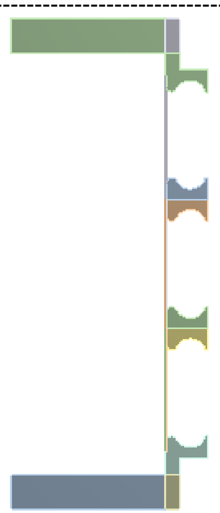

Figure 1. Geometric model of bellows hydroforming

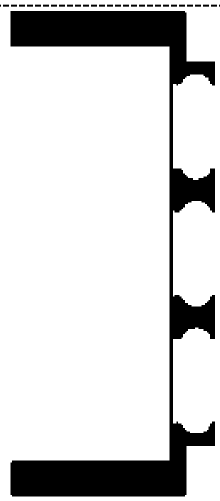

Figure 2. Mesh model of bellows hydroforming

As shown in Figure 1, the geometric model of bellows hydroforming is composed of tube blank, reinforcing rings and end plates.The dimension parameters of tube blank and reinforcing rings are shown in Table 1and Table 2. Considering the complicated stress-strain field of the tube blank during the forming process, each layer of the tube blank is divided into three layers of mesh in the thickness direction.The mesh size in the length direction is 1 mm, and the tube blank is mapped by quadrilaterals. The element type is an 8-node plane183. The completed mesh model is shown in Figure 2.

Table 1. Dimension parameters of tube blank

	Inner diameter /mm	Thickness/mm	Height /mm	The number of waves
Inner layer	1255	1.5	1519.82	3
Middle layer	1258	1.5	1519.82	3
Outer layer	1261	1.5	1519.82	3

Table 2. Dimension parameters of reinforcing ring

Length of the straight side of the bellows /mm	Lengthof reinforcing ring /mm	Thickness of reinforcing ring /mm	Radius of large arc /mm	Radius of small arc /mm
44	175.5	46.08	63.96	20

2.2. Material model

The material of tube blank

The bellows material is S30403, and its basic material parameters are listed in Table 3. During the hydroforming, the tube blank undergoes large deformation and large displacement during hydroforming. In this analysis, the material of tube blank is defined as an isotropic strengthening material. The isotropically strengthened S30403 stress-strain curve is shown in Figure 3.

Table 3. Material parameters of tube blank

Density ρ_1(kg/m3)	Tensile strength σ_{b1}(MPa)	Yield Strength σ_{a1}(MPa)	Elastic Modulus E_1(GPa)	Poisson's ratio V_1
7850	≥520	≥205	200	0.3

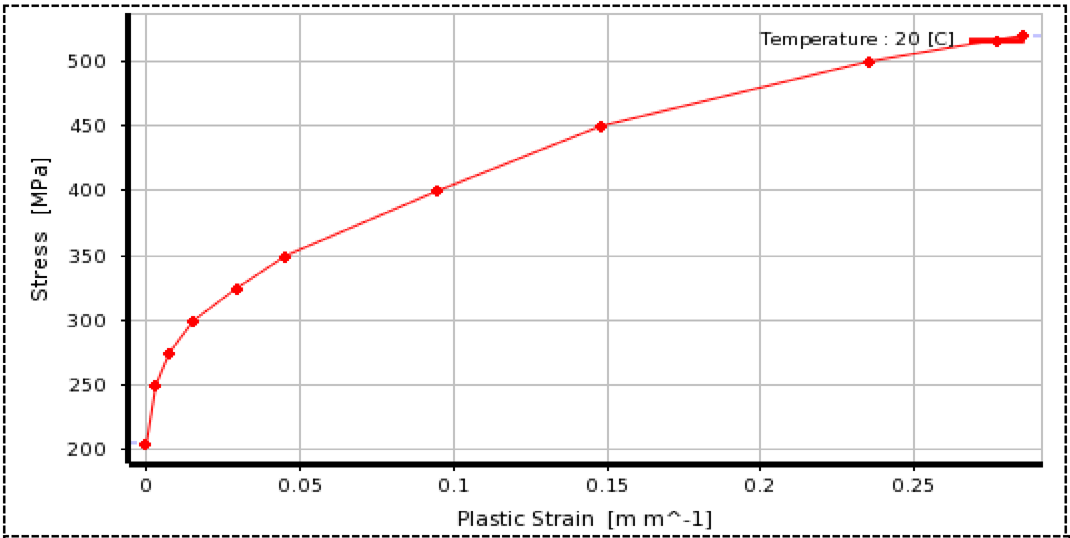

Figure 3. Isotropic strengthening S30403 stress-strain curve

The material of reinforced rings and molds. Q345R is selected as the material of reinforcing rings, and its material parameters are shown in Table 4. In the hydroforming process of the bellows, the deformation of the end plates used is small relative to the material of the tube blank, and thus, in this study, the end plates are considered as rigid body with the elastic modulus being 10 times that of ordinary carbon steel.

Table 4. Material parameters of reinforcing rings

Density ρ_2 （kg/m3）	Tensile strength σ_{b2}(MPa)	Yield Strength σ_{a2}(MPa)	Elastic Modulus E_2(GPa)	Poisson's ratio V_2
7850	480~630	≥305	206	0.3

2.3. Restrictions

Contact settings. During the hydroforming process of the bellows, the end reinforcing rings and the end plates are always in a conforming state, and the tube blank and the reinforcing rings are also permanently connected, so the bonding contact is set as shown in Figure 4.The outer side of the outer tube blank and the inner side of the reinforcing rings are only partially in contact at the initial stage of forming. As the forming process progresses, the tube blank gradually conforms to the mold, and the two surfaces are accompanied by tangential slip, so it is defined as frictionless contact. Similarly, the contact between the inner and outer layer is also defined as frictionless contact, as shown in Figure 5. Constraints and load settings The hydroforming process of the bellows is mainly divided into four stages, namely the drum phase, the forming phase, the pressure relief phase, and the unloading phase.There are two main types of loads applied to the tube blank.

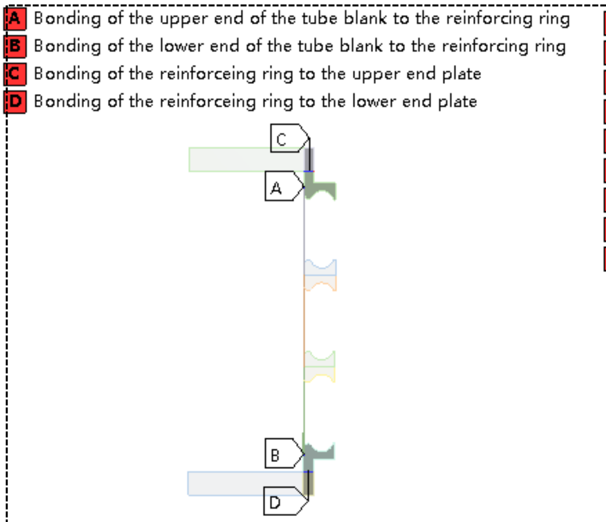

Figure 4. Bonded contact

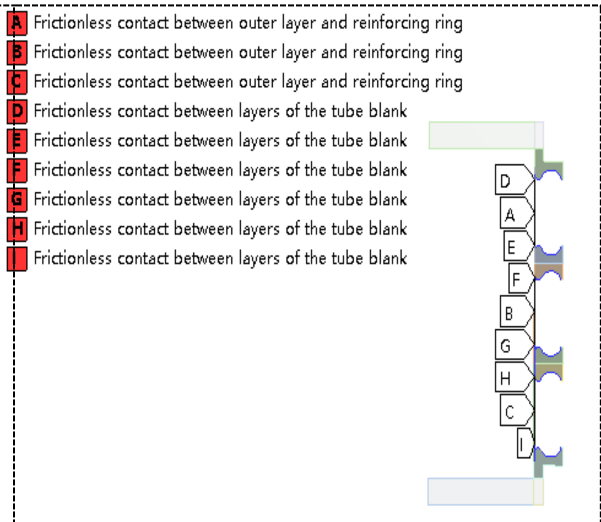

Figure 5. Frictionless contact

(1) Pressure loading: In the drum phase, the pressure increases linearly from 0 to 2.8 MPa. In the forming stage, the pressure is linearly increased from 2.8 MPa to 14.91 MPa. During the pressure relief phase, the pressure drops linearly from 14.91 MPa to 0. During the uninstall phase, the pressure remains at 0. This pressure acts on the inside of the tube blank as shown in A of Figure 6.

(2) Displacement loading: In the drum phase, the axial distance between the reinforcing rings is fixed by the support block, and the displacement of each reinforcing ring in the Y direction (see Figure 6) is 0. The displacement acting in the Y direction of the uppermost reinforcing ring is 939.82 mm in the forming stage, and the elastic springback amount of the bellows after unloading is 61 mm. During the whole forming process, the displacement in the Y direction of the lowermost reinforcing ring is always 0, and the action position of each displacement is as shown in Figure 6.

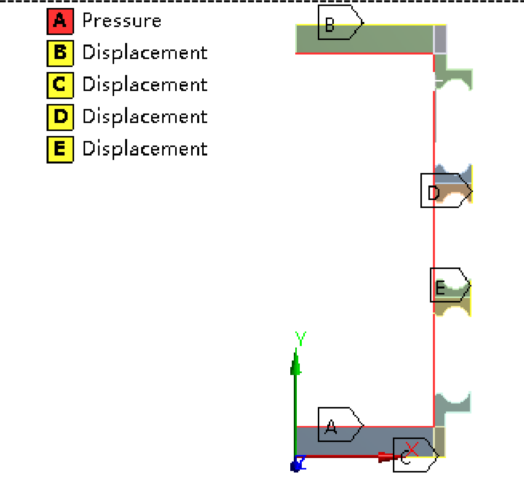

Figure 6. Loads and constraints

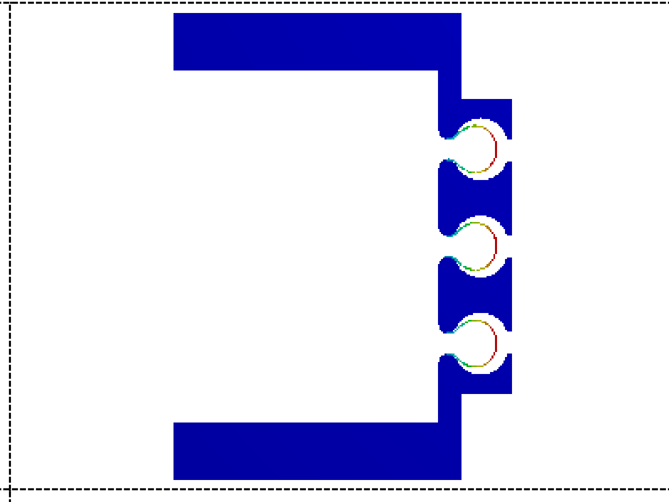

Figure 7. Shape of the bellows after hydroforming

3. Analysis of hydroforming simulation results

3.1. Equivalent stress distribution before and after unloading

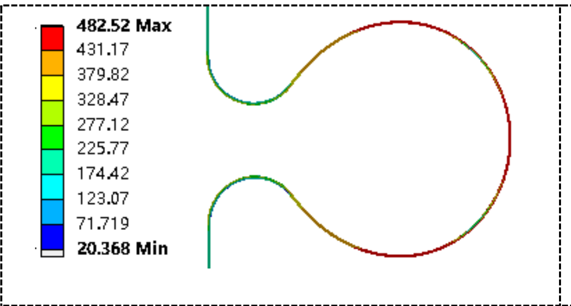

Figure 8. Equivalent stress before unloading.

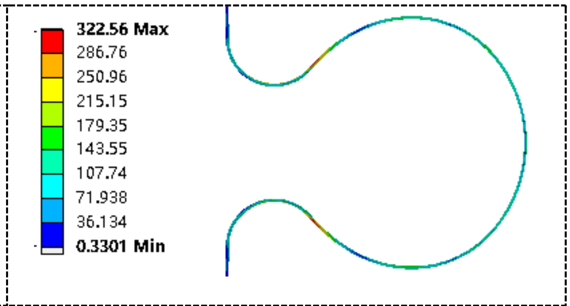

Figure 9. Equivalent stress after unloading.

The shape of the Ω-shaped bellows after hydroforming is shown in Figure 7. The simulation results show that the stress distribution at each wave of the Ω-shaped bellows after hydroforming is similar, so the stress field of only one wave is extracted for analysis. The von Mises equivalent stress distribution before unloading is shown in Figure 8. The von Mises equivalent stress distribution after unloading is shown in Figure 9. It is found that the maximum von Mises equivalent stress before unloading is mainly distributed on large arcs. And the maximum von Mises equivalent stress after unloading is mainly distributed at the transition between large arc and small arc. The maximum stress level after unloading is reduced by about 33.15% compared with that before unloading.

3.2. Equivalent total strain distribution before and after unloading

The equivalent total strain before and after unloading is shown in Figure 10 and Figure 11. It can be seen that the maximum von Mises equivalent total strain of each layer is about 0.2. The maximum value of the von Mises equivalent total strain before and after unloading is always distributed near the maximum displacement of the bellows along the wave height direction.

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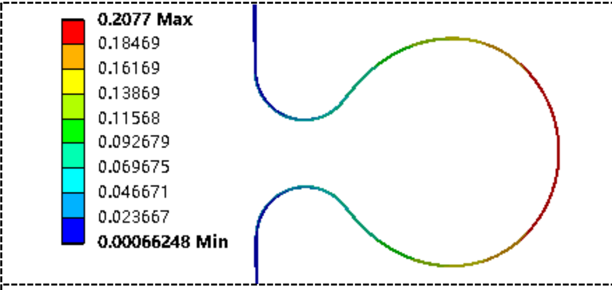

Figure 10 Equivalent total strain before unloading

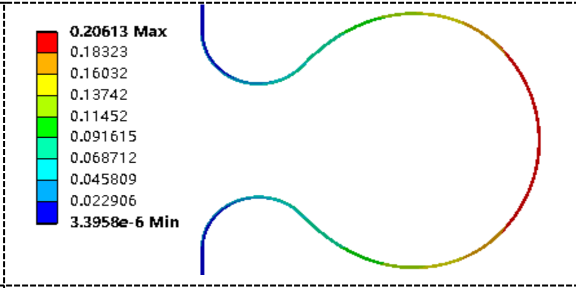

Figure 11. Equivalent total strain after unloading

3.3. Waveform parameters change before and after unloading

Elastic springback at wave height after unloading. The displacement of the Ω-shaped bellows in the wave height direction before and after unloading is extracted as listed in Table 5. Among them, "B" indicates before unloading, and "A" indicates after unloading.The difference between the displacement of the outer side of each layer before and after unloading reflects the elastic springback after unloading. The wave height elastic springback amount of the three-layer three-wave Ω-shaped bellows after unloading is shown in Table 6. It is found that the elastic springback amount of the three-layer three-wave Ω-shaped bellows after unloading is about 1.70 mm.

Table 5. Displacement of the Ω-shaped bellows at the wave height before and after unloading

	Outer side of the outer layer		Inner side of the outer layer		Outer side of the middle layer		Inner side of the middle layer		Outer side of the inner layer		Inner side of the inner layer	
	B	A	B	A	B	A	B	A	B	A	B	A
Wave 1	136.00	134.30	136.20	134.50	136.20	134.50	136.41	134.70	136.41	134.70	136.63	134.91
Wave 2	136.03	134.33	136.23	134.53	136.23	134.53	136.44	134.73	136.44	134.73	136.66	134.94
Wave 3	136.00	134.30	136.20	134.49	136.20	134.49	136.41	134.70	136.41	134.70	136.62	134.90

Table 6. Elastic springback at wave height after unloading of Ω-shaped bellows

	Outer layer	Middle layer	Inner layer
Wave 1	1.70	1.70	1.71
Wave 2	1.70	1.70	1.71
Wave 3	1.70	1.71	1.71

Thickness thinning rate at the peak after unloading.The difference in displacement between the inner wall and the outer wall of each layer of the Ω-shaped bellows after unloading is referred to as the thickness thinning amount. Table 7 lists the thickness thinning rate at the peak of the Ω-shaped bellows after unloading..

Table 7. Wall thickness thinning rate at the peak after unloading of the Ω-shaped bellows

	Outer layer	Middle layer	Inner layer	Outer layer	Middle layer	Inner layer
Wave 1	0.20	0.20	0.21	13.33%	12.67%	14.00%
Wave 2	0.20	0.20	0.21	13.33%	12.67%	14.00%
Wave 3	0.19	0.21	0.20	12.67%	14.00%	14.00%

Roundnessafter unloading.The roundness of the waveform after hydroforming of the Ω-shaped bellows is an important parameter for judging whether or not the bellows is successfully formed. If the roundness of the Ω-shaped bellows is insufficient, its load-bearing capacity is lowered and it cannot meet the requirements for use in the project. ASME-VIII-1 stipulates that in the manufacture of bellows, the ratio of twice the radius of the wave in the direction of the wave height to the height of the drum in the direction of the vertical wave height should be between 0.8 and 1.2. The closer the roundness is to 1, the better the waveform quality.Table 8 shows the roundness of each wave of the bellows after hydroforming. It is found that the roundness of each layer is between 0.8 and 1.2, which can meet the requirements of the project.

Table 8. Roundness of the Ω-shaped bellows after unloading

	Outer layer	Middle layer	Inner layer
Wave 1	1.098	1.096	1.095
Wave 2	1.112	1.111	1.110
Wave 3	1.104	1.103	1.102

4. Conclusions

In this paper, the finite element simulation software ANSYS Workbench is used to simulate and analyze the hydroforming process of a three-layer three-wave Ω-shaped bellows expansion joint.The stress and strain fields, wall thickness thinning rate at the peak and the roundness of the Ω-shaped bellows after hydroforming were analyzed.The conclusions are as follows:

(1) The maximum von Mises equivalent stress before unloading is mainly distributed on the large arc. After unloading, the maximum von Mises equivalent stress is mainly distributed in the transition between large arc and small arc with the maximum stress being reduced by about 33.15% compared with that before unloading.

(2) The maximum value of von Mises equivalent total strain is about 0.2 and always distributed near the maximum displacement of the bellows along the wave height before and after unloading.

(3) After unloading, the elastic springback amount of each wave of the bellows is about 1.70 mm.

(4) After unloading, the wall thickness thinning rate of the bellows can reach up to 14%.

(5) After hydroforming, all roundness of the bellows is between 0.8 and 1.2, which can meet the requirements of the project.

Acknowledgement

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