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Study on forming characteristics of natural bulging area of metal thin-walled tube under liquid impact forming

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Abstract : Liquid Impact Forming (LIF) is a new composite forming technology based on Tube Hydroforming (THF) technology, which changes the volume of mould cavity through impact load and rapidly generates internal pressure to realize tube forming. It does not need external pressure supply source, and it is low cost and high efficiency. In order to study the forming characteristics of the natural bulging area of thin-walled metal tubes under different model side lengths and different model closing velocities, the change of the cavity volume of thin-walled metal tubes under impact hydraulic bulging was firstly analyzed theoretically, and a mathematical model of internal pressure was established. Then the effects of different loading parameters on the internal pressure, bulging height and wall thickness distribution in the natural bulging area of thin-walled metal tubes were studied. Finally, through the comparison of finite element simulation analysis and experiment, it was found that the deviation between the experimental results and the numerical simulation was within 5%, which verified the accuracy and reliability of LIF. It also provides a certain theoretical research and application basis for the development of LIF of metal thin-walled tube.

Keywords: Liquid Impact Forming; Tube hydroforming; Metal thin-walled tube; Bulging height; Thickness distribution

1. Introduction

Tube hydroforming technology (THF) is an advanced manufacturing technology which bulges the tubes into the desired shape under the combined action of internal pressure and axial load[1, 2]. This technology saves materials, improves the strength and stiffness of parts, so it is mostly used in automobile, aircraft, home appliances and other fields[3, 4].

At present, many scholars have studied the forming characteristics of tubes under hydraulic bulging. Cui et al. [5, 6] found that the increase of external pressure could effects on the proportion of grain boundary, the number and size of microvoids and the microhardness of the transition area, so as to increase the critical effective strain in the transition area. Hwang et al. [7] proposed a mathematical model considering the sliding friction between the cylinder and the mould, and discussed the influence of the friction coefficient between the mould and the tube on the pressure and thickness distribution required for expansion forming. Based on the response surface method, Feng et al. [8, 9] analyzed the effects of axial feed, internal pressure, reverse loading displacement and friction coefficient on the minimum thickness of tube, branch tube height and ultimate fillet radius. The loading path was optimized by orthogonal test method, adaptive simulation and BP neural network control strategy based on genetic algorithm. Yuan et al. [10] proposed a new differential lubrication method in the process of T-tube hydroforming. It was also found that compared with the traditional uniform lubrication method, the differential lubrication method can avoid the wrinkling in the back of the main tube more effectively, increase the height of the branch tube, and reduce the thickening.

The LIF technology of thin-walled metal tubes has the advantages of higher forming efficiency, better forming performance, less process links and lower production cost, which has a wide application prospect in aviation, aerospace, chemical industry and other fields. Javad et al. [11] deformed the cross section of an aluminum tube into a hexagonal shape. The forming properties of hexagonal profiles were studied by tensile and three-point bending tests, and the plastic equivalent strain, the variation of the thickness of the profiles and the force needed in the forming process were obtained. Liu et al. [12, 13] theoretically analyzed the formation of internal pressure during axial impact hydraulic preforming and radial impact hydraulic forming of internal and external tubes, and established a mathematical model between the internal pressure and volume change in the tube cavity. Hu et al. [14] analyzed the basic theories of material condition of LIF, a dynamic plastic hardening model is derived based on the JC constitutive model. Li et al. [15] proposed a method to construct the thin-walled tube constitutive relation based on genetic algorithm. It was found that the deviations of the results obtained by using the genetic algorithm are all the least, so the dynamic plastic constitutive relation of the thin-walled tube can be predicted more accurately based on the genetic algorithm.

In this paper, the principle of LIF was introduced and the finite element model was established firstly. Secondly, numerical simulations of LIF were carried out based on ANSYS Workbench and DYNAFORM, the effects of different mould cavities and clamping speeds on the internal pressure, wall thickness distribution and bulging height in the natural bulging area of metal thin-walled tubes were discussed. Finally, the maximum internal pressure, bulging height and wall thickness distribution in the natural bulging area were obtained by impact hydraulic bulging test, which verified the reliability of the numerical simulation.

2. Principle of LIF and finite element model

2.1 Principle of LIF

The principle of LIF of metal thin-walled tubes is shown in Fig. 1: (1) Seal the tube and assemble it into the mould. (2) The liquid is passed into the tube cavity, and the pressure of the tube internal liquid is P_0 . (3) The upper and lower mould are closed gradually with exert impact load by the hydraulic press. The internal pressure P_i generated rapidly in the tube mould closing area under pressure is combined with the mould closing force F_{Ni} to produce compound deformation. The natural bulging area of the tube is only affected by the internal pressure to produce natural bulging. (4) At the end of mould closing, the

internal pressure in the tube is P_1 . The tube impact hydraulic bulging process is over, and the tube billet bulges into the required shape.



Fig. 1. LIF process of d metal thin-walled tubes

After the completion of tube bulging, the deformation area of the tube is the mould closing area and the natural bulging area, as shown in Fig. 2. The composite deformation of the tube in the mould closing area is mainly caused by the mould closing force and the internal pressure, while the natural bulging area is mainly caused by the internal pressure.





The shape of the metal thin-walled tube will be changed during the impact hydraulic bulging process. The section changes at different stages of the mould closing area are shown in Figure 3. Since the section of the mould area of the tube is of center-symmetric structure, one quarter of the arc $A_1M_1B_1$ is taken to study the deformation of the section of the mould area of the tube. Assuming that the mould cavity is completely filled by the thin-walled tube, only the volume change in the mould closing area is studied. The tube material is thin-walled tube, without considering the change of wall thickness. Since the mass and density of the tube do not change, the volume of the tube itself does not change. Therefore, the circumference of the billet does not change in the process of deformation, so the volume of the tube closing area is

$$V_{hi} = \frac{2\pi^2 - 8\pi}{(4 - \pi)^2} l_h h_i^2 + \pi r_1^2 l_h \tag{1}$$

where l_h is the length of clamping, h_i is the height of the clamping area, r_1 is the inner diameter of thinwalled tube.



Fig. 3. Diagram of section variation in mould - closing area of thin-walled metal tube

It is assumed that the natural bulging area is an ellipse, as shown in Fig. 2. The volume of the natural bulging area is the sum of the volume of the cylinder and the volume of the ellipsoid, without considering the volume changes of the connection area and the transition area is

$$V_{Zi} = \frac{4}{3}\pi \cdot \frac{l_z}{2} \cdot h_z \cdot h_z + \pi r_1^2 l_z = \frac{2}{3}\pi l_z h_z^2$$
(2)

β

 $+\pi r_1^2 l_z$ (2) where l_z is length of tube in natural bulging area, h_z is bulging height of tube in natural bulging area. The liquid can be compressed by external forces, and then the internal pressure will be generated spontaneously. According to the definition of the liquid volume compression factor

$$= -\frac{1}{V_0}$$
$$\cdot \frac{\Delta P}{\Delta V}$$
(3)

where β is the liquid volume compression factor, which is $\beta = 1/K_1$, K_1 is the bulk modulus. V_0 is the initial liquid volume in the metal thin-walled tube cavity. ΔP is the change of the internal pressure after the liquid is compressed, and $\Delta P_i = P_i - P_0$, where P_0 and P_i are the initial internal pressure and the internal pressure at a certain time in the tube, respectively. Therefore, the equation (3) can also be expressed as

$$P_i = P_o - \frac{\Delta V_i \cdot V_0}{K_1} \tag{4}$$

According to the geometric relationship between Fig. 2 and Fig. 3, the volume change of the cavity in the mould closing area and the natural bulging area of the tube is

$$= V_{hi} + V_{Zi}$$

$$- V_{0}$$

$$= \frac{2\pi^{2} - 8\pi}{(4 - \pi)^{2}} l_{h} h_{i}^{2} + \pi r_{1}^{2} l_{h} + \frac{2}{3} \pi l_{z} h_{z}^{2} + \pi r_{1}^{2} l_{f} - \pi r_{1}^{2} l_{0}$$

$$= \frac{2\pi^{2} - 8\pi}{(4 - \pi)^{2}} l_{h} h_{i}^{2}$$

$$+ \frac{2}{3} \pi l_{z} h_{z}^{2}$$
(5)

 $\Delta V_i(T)$

where l_0 is initial total length of tube deformation area. According to equations (4) and (5), the internal pressure of the thin-walled metal tube can be obtained as

$$=P_{o} - \frac{\left[\frac{2\pi^{2} - 8\pi}{(4 - \pi)^{2}}l_{h}h_{i}^{2} + \frac{2}{3}\pi l_{z}h_{z}^{2}\right]\pi r_{1}^{2}l_{0}}{K_{1}}$$

$$\tag{6}$$

2.2 Finite element model

To explore the forming characteristics of the metal thin-walled tube under impact hydraulic load, the natural bulging area of tube was analyzed under the same loading conditions, the same initial parameters including the material properties, the initial wall thickness. The model established by SolidWorks is shown in Fig. 4. The geometric parameters and mechanical properties of the model are shown in Table 1.



Lower mold

Fig. 4. Fin	ite element	model of	tubes	and LIF	device
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	Table 1 Geometrical parameters and mechanical properties of tubes						
No.	Parameters and symbols	Numerical value					
1	Length of tube L (mm)	180					
2	Length of natural bulging area l_h (mm)	60					
3	Length of Clamping area l_z (mm)	60					
4	Initial diameter D (mm)	38					
5	Initial wall thickness t (mm)	0.7					

6	Yield strength σ_s (MPa)	205
7	Tensile strength σ_b (MPa)	620
8	Strength factor K	1708.4
9	Hardening index n	0.47

2.2.1 ANSYS Workbench simulation setup

Since the internal pressure of metal thin-walled tube during LIF process is a non-linearly changing pressure generated during the forming process, it is necessary to obtain the tube forming loading path through the transient dynamics module in ANSYS Workbench.

The material properties are shown in Table 2. The upper and lower moulds, the left and right positioning rings and sealing plugs are set as rigid bodies, and the inner and outer metal thin-walled tubes are set as deformed bodies.

Table 2 Material properties of the finite element model						
Parameter	Tube	Mould	Locating ring	Sealing plug		
Material	SUS304	Cr12	45#	Polyurethane		
Density ρ (kg/m ³)	7930	7780	7850	1020		
Young's modulus E (Pa)	2.07E+11	2.11E+11	2.09E+11	3E+10		

Table 2 Material properties of the finite element model

Set three moulds (side length 28×28mm, 29×29mm and 30×30mm) and five clamping speeds (10mm/s, 20mm/s, 30mm/s, 50mm/s and 70mm/s) as simulation conditions, the corresponding clamping time and simulated maximum internal pressure are shown in Table 3.

No.	Mould side length <i>a×a</i> (mm)	Clamping height <i>h</i> (mm)	Clamping speed v (mm/s)	Clamping time t (s)	Simulated maximum internal pressure <i>P_{max}</i> (MPa)
1			10	0.7070	24.99
2			20	0.3535	24.99
3	28×28	7.070	30	0.2357	24.91
4			50	0.1414	24.99
5			70	0.1010	24.95
6			10	0.6365	23.93
7			20	0.3183	23.93
8	29×29	6.365	30	0.2122	23.93
9			50	0.1273	23.92
10			70	0.0909	23.91
11	20×20	E (E E	10	0.5655	21.95
12	30×30	5.655	20	0.2828	21.95

Table 3 Simulation scheme of LIF

13			30	0.1885	21.96
14			50	0.1131	21.95
15			70	0.0807	21.95
16			10	0.4950	20.52
17			20	0.2475	20.51
18	31×31	4.950	30	0.1650	20.53
19			50	0.0990	20.50
20			70	0.0707	50.51

2.2.2 DYNAFORM simulation setup

The model in Fig.4 is imported into DYNAFORM. BT shell element is used to divide the mesh. The deformed tube is divided into 2×2 quadrilateral elements, and the rigid body is divided into 3×3 quadrilateral elements. The friction coefficient is set to 0.05. Finite element model meshing is shown in Figure 5.



Fig. 5. Finite element model meshing

The loading path was set as nonlinear loading. The curve of internal pressure and time was obtained by ANSYS Workbench simulation. The internal pressure obtained by ANSYS Workbench simulation was converted into CSV file and imported into DYNAFORM software, as shown in Fig. 6. The node constraint is set as Z-guide (XY), and there are 3712 constraint points in total. The deformation area includes the mould closing area and the natural bulging area of the tube, and there are 6844 deformed nodes in total.



Fig. 6. Loading path imported into DYNAFORM software

3 Numerical simulation analysis

In order to study the forming properties of the natural bulging area of thin-walled metal tubes under LIF, the influence of different loading parameters (mould side length and mould closing speed) on the forming properties of the natural bulging area of thin-walled metal tubes, such as internal pressure, wall thickness distribution and bulging height, was systematically analyzed.

3.1 Internal pressure

Numerical simulation analysis was carried out for tube LIF under different mould closing speeds and mould side lengths. Based on ANSYS, the tube internal pressure curve was obtained, as shown in Fig. 7. It is not difficult to find from the figure:

(1) Under the same mould, with the increase of mould closing speed, the mould closing time is shorter, the rate of internal pressure rising is larger, and the tube forming efficiency is higher.

(2) At the beginning of mould closing, the internal pressure of the tube changes slowly. In the middle and late period of mould closing, the growth rate of internal pressure gradually increases, and the faster the speed, the greater the growth rate of internal pressure. The reason is that at the early stage of mould closing, the volume change of the tube cavity is small, the liquid compression is small, and the internal pressure increases slowly. With the impact load, the mould is closed, the volume change of the tube cavity increases, the liquid compression is large, and the internal pressure of the tube increases rapidly.

(3) At the same closing speed, the smaller the mould length, the greater the internal pressure. Under the same mould, the internal pressure has no obvious relation with the closing speed,. When the mould closing speed is 10mm/s and the mould side length is 28×28mm, the maximum limit internal pressure is 24.99MPa, and when the mould side length is 31×31mm, the minimum limit internal pressure is 20.53MPa, the difference between them is 4.46MPa. The reason is that the fluid pressure will increase with the increase of the cavity volume change of the tube, and the cavity volume change is proportional to the closing height, and has no relation with the closing speed.



Fig. 7. Simulate internal pressure curves

3.2 Bulging height

Bulging height, as one of the important parameters to verify the formability of tube, is mainly affected by mould side length, mould closing speed and liquid pressure. In this section, the bulging height in the natural bulging area of the tube is analysed as shown in Fig. 8.



Fig. 8. The bulging height of the natural bulging area of the tube

Through numerical simulation analysis of tube LIF under different mould closing speeds and mould side lengths, the bulging height of the natural bulging area of the tube in the last frame before the completion of bulging was obtained as shown in Fig. 9. It is not difficult to find from the figure:

(1) When the moulds are the same, the bulging height of the natural bulging area has good consistency at different closing speeds, which show that the closing speed is not the most important factor

to bulging height.

(2) At the same mould closing speed, the smaller the mould, the greater the bulging height of the natural bulging area of the thin-walled metal tube. The reason for this is that the fluid pressure is increased with the increase of the cavity volume change of the tube, and the cavity volume change is proportional to the closing height.



Fig. 9. Effects of different mould cavities and clamping speeds on tube bulging height

3.3 Thickness distribution

The location of wall thickness collection points is shown in Fig. 10.



Fig. 10. Wall thickness data acquisition section

Through numerical simulation analysis of tube LIF under different mould closing speeds and mould side lengths, the wall thickness of the natural bulging area of the tube in the last frame before the completion of bulging was obtained, as shown in Fig. 11. It is not difficult to find from the figure:

(1) The wall thickness distribution of each collection point has a good consistency, and has good symmetry along the horizontal section of the tube.

(2) Under the same mould side, the wall thickness thinning rate of the natural bulging area of the tube with the speed of 70mm/s is the smallest, while the wall thickness thinning rate of the natural bulging

area of the tube with the speed of 10mm/s is the largest. The reason for this is that under the same mould, the forming efficiency is proportional to the speed. The longer the forming time is, the slower the fluidity of the tube will be, and the smaller the wall thickness will be.

(3) Under the same mould closing speed, the thinning rate of natural bulging area of tube with mould side length of 31×31 mm is the smallest, while the thinning rate of natural bulging area of tube with mould side length of 28×28 mm is the largest. The reason is that the smaller the length of the mould side is, the smaller the change amount of the mould cavity is. Under the condition of small cavity and large internal pressure, the tube bulging is more full, resulting in more serious local thinning and thickening of the tube.



Fig. 11. The effect of different mould cavities and clamping speeds on the tube wall thickness (a) $a=28\times28$ mm, (b) $a=29\times29$ mm, (c) $a=30\times30$ mm, (d) $a=31\times31$ mm

4 Experimental verification

4.1 Experimental setup

YL32-200TA four-column hydraulic press is adopted to carry out stamping experiment. It can be adjusted a large range of working speed. The LIF apparatus is used to obtain the ideal bulging shape, which is mainly composed of upper and lower templates, upper and lower moulds, guide bushings, guide posts and springs, as shown in Fig. 12. Its working process is as follows: (1) Install the sealing column with hollow hole on both ends of the liquid-filled bolt, and make one end of the sealing column contact the step of the liquid-filled bolt. (2) Put the tube into both ends of the liquid-filling bolt that has been assembled with the sealing column, and make both ends of the sealing column all into the inside of the

tube. (3) Put the positioning snare into both ends of the tube, lock it with nuts, and connect and fix it with the liquid-filling bolt with short hole and manual hydraulic pump. (4) Place the assembled tube on the mould.



Fig. 12. Hydraulic press and tube forming device

(a) Hydraulic presses, (b) Forming apparatus, (c) Physical drawing of tube and forming device

Three mould lengths ($a = 28 \times 28$ mm, $a = 29 \times 29$ mm, $a = 30 \times 30$ mm and $a = 31 \times 31$ mm) were used to carry out LIF tests on metal thin-walled tubes at three closing velocities (10mm/s, 50mm/s and 70mm/s). The SS304 thin-walled tube was used in this test. Its geometrical parameters are shown in Table 4.

Table 4 Geometric parameters of tubes for the experiment						
	Length L	Initial	Initial wall	Length of natural	Length of	
Materials	(mm)	diameter D	thickness t	bulging area l_z	Clamping area l_h	
		(mm)	(mm)	(mm)	(mm)	
SS304	180	38	0.7	60	60	

Table 4 Geometric parameters of tubes for the experiment

4.2 Results and discussion

Through the LIF experiment part of the tube forming parts are obtained as shown in Fig. 13. The data include the internal pressure, the bulging height and the wall thickness distribution in the natural bulging area of the tube. The location of data selection is shown in Figure 14.



Fig. 13. Formed tubes in experiments



Fig. 14. Location of test data selection

4.2.1 Internal pressure

The liquid pressure value of the tube is observed by the pressure gauge, as shown in Table 5. It can be known from the test that in the SS304 thin-walled tube LIF under four kinds of moulds and three kinds of speeds the smaller the mould side length, the greater the liquid pressure value. And the maximum liquid pressure value has no direct relationship with the speed. The maximum liquid pressure measured values have good consistency between the test and the simulated, the deviation is within 5%.

Table	5	Experiment	Internal	pressure
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		1	1	
No.	Mould side length $a imes a$ (mm)	Clamping height h (mm)	Clamping speed v (mm/s)	Experiment maximum internal pressure P _{max} (MPa)
1			10	24.9
2	28×28	7.070	50	24.7
3			70	24.7
4			10	23.9
5	29×29	6.365	50	23.6
6			70	23.8

7			10	22.9
8	30×30	5.655	50	22.8
9			70	22.6
10			10	21.1
11	31×31	4.950	50	21.5
12			70	21.4

4.2.2 Bulging height

The bulging height of natural bulging area of SS304 thin-walled tube is shown in Fig. 15. It is not difficult to find from the figure:

(1) Under the same mould, there is no obvious relation between the mould closing speed and the bulging height of the natural bulging area of the tube.

(2) At the same mould closing speed, the smaller the mould, the greater the bulging height of the natural bulging area of the thin-walled metal tube. When the mould closing speed is 10mm/s and the mould side length is 28×28 mm, the maximum bulging height of the natural bulging area of the tube is 42.06mm, and the minimum bulging height of the natural bulging area of the tube is 38×88 mm when the mould side length is 31×31 mm.

(3) It has good consistency from the conclusions obtained between the experimental and numerical simulation. The data deviation of bulging height in the natural bulging area is less than 5%.



Fig. 15. Effects of different mould cavities and clamping speeds on tube bulging height

4.2.3 Thickness distribution

The wall thickness of natural bulging area of SS304 thin-walled tube is shown in Fig. 16. In the figure. H_S is the wall thickness of natural bulging area of tube. It is not difficult to find from the figure:

(1) Under the same mould closing speed, the thinning rate of natural bulging area of tube with mould side length of 31×31 mm is the smallest, while the thinning rate of natural bulging area of tube with mould side length of 28×28 mm is the largest.

(2) Under the same mould side, the wall thickness thinning rate of the natural bulging area of the tube with the speed of 70mm/s is the smallest, while the wall thickness thinning rate of the natural bulging area of the tube with the speed of 10mm/s is the largest.

(3) It has good consistency from the conclusions obtained between the experimental and numerical simulation. The data deviation of bulging height in the natural bulging area is less than 6%.



Fig. 16. The wall thickness distribution at different mould cavities and clamping speeds (a) $a=28\times28$ mm, (b) $a=29\times29$ mm, (c) $a=30\times30$ mm, (d) $a=31\times31$ mm

5 Conclusions

In this paper, the theoretical analysis, numerical simulation and experimental study on the forming of thin-walled metal tubes were carried out based on the LIF. The influence of liquid pressure and different load parameters on the forming performance of the natural bulging area of the thin-walled metal tube was analyzed and verified by the LIF test. The main research conclusions are as follows:

(1) Based on the relationship between the volume change of the tube cavity and the liquid pressure, a mathematical model of the liquid pressure of the thin-walled metal tube was established.

$$P_i = P_o - \frac{\left[\frac{2\pi^2 - 8\pi}{(4 - \pi)^2} l_h h_i^2 + \frac{2}{3}\pi l_z h_f^2\right] \pi r_1^{\ 2} l_0}{K_1}$$

(2) Under the same mould length, with the increase of mould closing speed, the mould closing time is shorter, the rising rate of internal pressure is larger, and the tube forming efficiency is higher. At the early stage of mould closing, the internal pressure value of the tube changes slowly, but in the middle and late stage of mould closing, the growth rate of the internal pressure gradually increases, and the faster the speed, the greater the growth rate of the internal pressure.

(3) When the edges of the mould are the same, there is no obvious correlation between the mould closing speed and the bulging height in the natural bulging area of the tube. At the same closing speed, the smaller the length of the mould side, the greater the bulging height of the natural bulging area.

(4) The wall thickness distribution of each collection point has a good consistency, and has good symmetry along the horizontal section of the tube. Under the same mould closing speed, the thinning rate of natural bulging area of tube with mould side length of 31×31mm is the smallest, while the thinning rate of natural bulging area of tube with mould side length of 28×28mm is the largest. Under the same mould side, the wall thickness thinning rate of the natural bulging area of tube with the speed of 70mm/s is the smallest, while the wall thickness thinning rate of the natural bulging area of the tube with the speed of 10mm/s is the largest.

Declarations

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and material (Not applicable)

Code availability (Not applicable)

Authors' contributions

Xiangwen Fan: Conceptualization, Methodology, Investigation, Software, Validation, Writing - original draft, Writing - review & editing, Visualization. Jianwei Liu: Conceptualization, Overall planning, Supervision, Writing - review & editing, Project administration, Funding acquisition. Zhu Xiao: Supervision, Technical support, Writing - review & editing. Huiping Liang: Validation, Formal analysis, Supervision. Changying Sun: Resources, Investigation, Software, Formal analysis, Validation. Fengshou Tian: Resources, Investigation, Formal analysis, Data curation.

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