Optimal Parameter Study of the External Inverting Die

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**Abstract:** In the external inverting process of thin-walled circular tube, buckling instability often occurs in the straight line section of thin-walled tube due to the size mismatching of forming die. Based on LS-DYNA971, the finite element modeling was built up and a series of simulation calculations were conducted about the external inverting process of thin-walled circular tubes on two circular arc dies under axial compression. The inverting plastic deformation of a Q235 steel thin-walled tube with an outer diameter of 60mm and a wall thickness of 2mm was reproduced on two die types with different fillet radii. The simulation results show that the optimal induced fillet radii of the dies is 10.7±0.1m, and meanwhile the thin-walled tube head has good formability in the early stage, which is convenient for the subsequent shape operation of the invertube. This paper provides a method reference for the die structure design used for inverting the thin-walled tube.

1. **Introduction**

In previous studies, great attention has been paid to the fact that the huge impact energy generated by the collision is digested and absorbed on the fast moving mechanism in a relatively gentle way, so as to protect the driver and passenger from fatal injury, especially on the automobile, locomotive and spacecraft. Many experts and engineers around the world have done a lot of research on various thin-walled structures and energy absorption devices [1-5]. General motors company has applied the inverting mechanism to the steering column of cars [6], which plays a good role in protecting the chest of passengers in the event of a collision. The energy absorption appliance of the invertube has the advantages of small size, light weight, easy installation and high energy absorption ratio, so it has been widely used [7-8].

The crashworthiness structure design is to reduce the peak deceleration to protect passengers from fatal injuries. In the process of collision, most of the traditional thin-walled metal structures also have a sharp load fluctuation when subjected to axial compression. When used as an energy absorption device for rail vehicles, the load transferred to the passengers changes significantly, which is not good for passenger safety, as shown in curve b and c in Fig.1. If the acceleration is kept constant during the impact, as shown in Fig.1-a, it will not cause the serious passenger injury subjected to the powerful inertial impact. At present, the section shapes and working principle of the inversion tubes are slightly different, mainly including the four types in Fig.2. This paper will focus on the parameter research of forming die in Fig.2-c.
Fig. 2 Four types of invertube forming processing

2. Forming die structure and inverting process modeling

2.1 Invertube die structure

Taking the thin-walled tube (Φ60*2mm) as the research object, a die structure A in Fig. 3 was designed, setting only 1/4 circular arc section as invertube inverting guide, fillet radius r. Huang Zaowen et al. [10], based on the result of the theoretical research of Φ50*1.5mm aluminium tube, argued that the optimal critical radii \( r_i \) existed on a specified invertube die. When \( r = r_i \), the circular tube suffers the minimum inversion load \( P \). The calculation formula of the critical radius \( r_i \) is

\[
r_i = \left[ \sqrt{\left( \frac{2D_m}{t_0} \right)^3} + \frac{3t_0}{4} \right]^{\frac{1}{3}}
\]

where \( r_i \) is the optimal radius of inversion die. \( D_m \) is the medium diameter of the tube, and \( t_0 \) is the wall thickness of tube.

According to formula (1), the critical inversion radius of 5.3mm can be calculated, combined with the results of the actual inversion test and the successful case [11], the research scope of the die fillet radius parameters is extended to the range of 4~12mm.

Fig. 4 shows the die structure Type B, with 1/2 circle as the induced inversion deformation zone. Artificially adding an upward guiding radius \( r \), can provide an upward inducing deformation for the tube after it expands circumferentially, which is more conducive to the invertube forming.

2.2 Finite element models

The basic dimensions and material mechanical properties of circular tube are listed in Table 1. According to the above-mentioned dimensions of tube and the corresponding two kinds of die structures, the finite element models corresponding to tube and inversion dies are established in Hypermesh13.0, as shown in Fig. 5 and Fig. 6. The total element number in the model is 113,552, including 56,400 hexahedral elements and 57,152 shell elements. The basic element size is 1.0mm.

All the nodes on the top 1/5 of tube were applied with an axial displacement load. The total displacement was 100mm, and the motion velocity was 3.333m/s. The effect of dynamic strain rate of material was not considered in finite element models. Only one layer of rigid shell element was built on the upper surface of the die, and the shell element type was the same as the outer surface elements’ of the tube. The material model of die was *Mat_rigid (Mat 20), and rigid shell elements were fully constrained. *Contact_forming_surface_to_surface_ID was used to establish face-to-face contact pairs between the outer surface of tube and the upper surface of die. Static and dynamic friction coefficients were both set as 0.2. A cross section was set by using *Database_cross_section_plane_ID at the top 1/10 of the tube to extract the squeezing force between the tube and the die during the
inversion process. The total calculation time was set as 0.03s. The mass scaling technology was used to reduce the CPU running time, meanwhile the mass increase was controlled within 5%. After the relevant calculation control parameters were set, the *.k file was imported into Lsdyna 971 codes for numerical calculation.

Tab.1 Dimensions of tube blanks and mechanical properties of materials

| Material type | Tube Height $h$ /mm | Outer Diameter $D$ /mm | Wall Thickness $t_0$ /mm | Elongation /% | Yield Strength $\sigma_{0.2}$ /MPa | Shear Modulus $G$ /MPa | Friction Coefficient |
|---------------|---------------------|------------------------|--------------------------|--------------|-----------------------------------|----------------------|---------------------|
| Q235          | 300                 | 60                     | 2                        | 25           | 235                               | 500                  | 0.2                 |

Fig.5 Finite element model A  
Fig.6 Finite element model B

3. The discussion of simulation results
In the inversion process simulation, it was assumed that the material did not occur to tear. By comparing the initial inverting plastic deformation results with several small inducing radii of die, it shows that the lesser the die radius is, the bigger the inverting difficulty is. When the die radius is larger, the tube head continued to expand uniformly all around and move downward until it touched the lowest point of the die surface. The more the tube head inverts, the more conducive the later fine shaping is conducted.

Fig.7 shows the inverting deformation modes at the moment when the straight line section of the tube starts to buckle in the die A with different fillet radius. Compared with $r = 9.0$, 10.0 and 10.7mm, the inverting performance of the tube head corresponding to the radius $r = 4.0$, 5.2 and 8.0mm of the die corner are significantly better. When $r = 4.0$ and 5.4mm, the tubes were compressed and the tube head only expanded a little circumferentially, without any inverting deformation. It indicates that there is a significant difference between the die radius predicted by the Huang’s theory and the real die radius from simulation results. According to the comparison of the simulation results, if the fillet radius of the die A is between $r = 4.0$–8.0mm, the inversion will not finish. When $r \geq 9.0$mm, the inverting deformation mode was gradually improved, showing a larger trend of natural inverting forming. When $r = 10.0$mm, the inversion tendency of tube was more obvious. The buckling of tube when $r = 10.7$mm did not occur under these simulation conditions. After that, supplementary verifications analysis were carried out for the cases $r = 10.9$mm and 11.1mm. There was almost no differences observed between $r = 10.7$mm and $r = 10.9$mm. However, when $r = 11.1$mm, compared with $r = 10.9$mm, obviously the buckling was more likely to occur in the straight line segment of tube. It can be seen that the fillet radius continues to increase, and the inverting process is more inclined to fail. It is speculated that the ideal fillet radius of die A is within the range of $10.7 \pm 0.1$mm.
Fig. 7 Simulation results of tubes on the die A

Fig. 8 shows the simulated inverting deformation modes using the die B at the moment when the straight line segment of the tube starts to buckle. The inverting radii of the die B are 5.0, 6.0, 7.0, 10.5, 10.6, 10.8, 11.2 and 11.5mm, respectively. Obviously, when \( r = 5.0, 6.0 \) and 7.0mm, the inverting deformation modes of the tube are not ideal. When a small section of the head of the tube is still expanding circumferentially, the straight line section buckles at the same time. It means that the external inverting process of tube will go worse. Starting from \( r = 10.5 \)mm, the tube inverting deformation modes improved significantly. By observing the inverting deformations of the tube head of \( r = 10.6 \)mm and 10.8mm, under the same constraint conditions, the degree of the tube inversion of \( r = 10.5 \)mm was less than that of \( r = 10.6 \)mm and 10.8mm. When \( r = 10.6 \)mm and 10.8mm, the inversion success trend became more and more obvious, and both inverting deformations of the tube head were the same almost.

In addition, the buckling of the straight line segment with \( r = 11.2 \) and 11.5mm occurs earlier than that with \( r = 10.8 \)mm, so the tube inverting is more likely to failure. Therefore, it can be speculated that for the die B, the optimal fillet radius \( r \) is 10.7±0.1mm, which is consistent with the research conclusion of the fillet radius of the die A.

Considering the die manufacturing cost, the die A is simple and more cost-effective. Meanwhile, a big advantage of die B is that the deformation section of the invertube head can be appropriately extended upward, which is more convenient for subsequent head shaping and welding installation for the invertube.

Fig. 8 simulation results of tubes on the die B
4. Conclusions
In this paper, the Q235 seamless thin-walled tube with an outer diameter of 60mm and a wall thickness of 2.0mm was taken as the research object. The influencing effect of different fillet radii on the inverting plastic deformation of thin-walled tube was studied by using two section types of inverting dies A and B. The results show that when the fillet radius is smaller than 10.0mm, the tube head can not invert normally.

When the fillet radius of the die is about 10.7mm, the tube head expands smoothly and inverts sufficiently before the straight line section buckles. The tube head often slides across the lowest point of the circular arc of the die, but the total inverting height of the tube head is relatively small.

Furthermore, it can be seen from the optimal fillet radius of the die for tube inverting differs greatly from the theoretical values calculated from the formula (1), the simulation predicting value is about twice as big as the theoretical value. The research results from this paper can provide technical and method references for designing the die structure of thin-walled inversion tube.

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