Study of the External Inverting Process of the Mild Steel Thin-walled Tube

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Abstract: The invertube is an ideal energy absorber to improve the crashworthiness of the vehicle skeleton body structure, but the low cost mild steel thin-walled tube often suffers some serious tearing phenomena in the external inverting process on the forming die. In order to investigate the interference factors of external inverting deformation, the optimum parameter of die structure design and the axial resistance force level of thin-walled tube in the external inverting process, a nonlinear finite element explicit dynamic codes were adapted to simulate the plastic inverting process of a mild steel thin-walled tube. The tube has the outer diameter of 60mm and the wall thickness of 2.0mm. The external inverting processes were conducted upon two kinds of round corner dies. Based on the results of previous theoretical analysis, the radius range of the corresponding die were obtained by theoretical calculation. The two die section forms and a series of dies with different round corner radii were also designed to build finite element simulation models. The inverting simulation results show that the optimal induced radii of the dies are within the range of 10.5-11.0mm. Meanwhile, it can be seen that the mild steel thin-walled tube has good formability in the early stage, which is convenient for the subsequent fine shaping of the invertube end. Moreover, the die bears less axial extrusion force, which is conducive to the improvement of the working life of the die. In the last, an ideal alloy steel die with the optimal rounded radius of 10.7mm was manufactured and used to verify the feasibility to finish the invertube manufacturing using mild steel thin-walled tubes. It provides a good simulation technology reference for the die structure design to realize the external inverting of the mild steel thin-walled tube.

1. Introduction
In previous studies, many concerns have been paid to the fact that the huge impact energy generated by the collision can be digested and absorbed on the fast moving mechanism in a relatively gentle way, so as to protect the driver and passenger from deadly injury, especially on the automobile, locomotive and spacecraft [1]. Many experts have done numerical research on various energy absorption devices. Alexander [2] studied the axial compression performance of circular thin-walled tubes. In the past investigations, people attach great importance to the fact that the motion mechanism digests and absorbs the huge impact energy produced by the collision in a mild way when the collision occurs, and then to protect against the driver and passenger. Abramowicz [3] and Chen [4] studied the comparison of energy absorption ratio between square tube and circular tube under high speed impact. Zhang [5] studied the axial energy absorption characteristics of metal multicellular tubes, and concluded that the en-
Energy absorption efficiency was higher than that of metal foam-filled tubes under the same mass. Meanwhile some new configuration of circular stepped tubes reinforced with external stiffeners and thick-walled metal tubes with wide external grooves were studied by simulation to improve energy absorption characteristics under axial impact [6-8].

The problem of automobile crash safety structure design is to reduce the pinnacle type deceleration to protect passengers from fatal injuries[9]. The peak pulse usually appears in the collision process. The load wave of most traditional thin-walled metal structures under axial compression is quite intense. When used as the rail vehicle energy absorption device, the load transmitted to the occupant changes significantly, which is not conducive to personal safety. If a low level acceleration is kept constant during the impact, it will not cause the serious passenger injury subjected to the powerful inertial impact. At present, the section shapes and working principle of the invertubes are slightly different, mainly including the four types in Fig.1 [10]. This paper will focus on the parameter research of the forming die listed in Fig.1-c.

2. Forming die structures and inverting process modelings

2.1 Inverting die structures
Taking the thin-walled pipe (Φ60 *2mm) as the research object, the die structure A in Fig. 3 is designed, and only 1/4 arc section is set as the inverse guide rail of the pipe. Based on the theoretical study of Φ50 *1.5mm aluminum tube, Huang Zaowen [11] proposed that there exists an optimal critical radius Ri on a specific inverted tube mold. When r = ri, the circular tube suffers the minimum inversion load P. The calculation formula of the critical radius ri (1) is

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

(1)

Where ri is the optimal radius of inversion die. Dm is the medium diameter of the tube, and t0 is the wall thickness of the tube.

According to the formula(1) and the selected thin-walled tube dimensions, the critical inversion radius is 5.3mm. Combined with the results of the actual inversion tests and the successful case [12], the ideal research scope of the die fillet radius is limited to the range of 4~12mm.

Fig.2 and Fig. 3 shows the A-type and B-type die structure. In the die B, the inverted deformation induced zone is 1/2 turn. Artificial increase of upward guiding radius r can cause upward induced deformation after circumferential expansion of the tube, which is more conducive to reverse tube forming.
3. Finite Element Models

According to the corresponding two kinds of die structures, the corresponding finite element models were established in Hypermesh13.0, as shown in Fig. 4 and Fig.5. The total element number in the finite element model is 113,552, including 56,400 hexahedral elements and 57,152 shell elements. The basic element size is 1.0mm [13].

In the finite element model, the tube was meshed with hexahedral solid elements whose element type was fully integrated quadratic 8 node element with nodal rotations. For building the contact pair between tube surface and die, the outer surface of the tube was overall enveloped with the quadrilateral shell elements whose thickness was 0.1mm. The shell element type was fully integrated shell element. The material model of tube was *Mat_piecewise_linear_plasticity (Mat 24). Axial displacement loads are applied to all nodes in 1/5 of the pipe top. The total axial displacement is 100mm, and the motion velocity is 3.333m/s. The effect of dynamic strain rate of material was not considered in finite element models. The top surface of the mold is also quadrilateral shell element, the type of quadrilateral shell element is the same as the outer surface element of the cylinder. Material model is *MAT_RID (MAT 20). Use the contact command *Contact_forming_surface_to_surface_ID to create a face-to-face contact pair between the outer surface of the tube and the upper surface of the mold. The static and dynamic friction coefficients were set at 0.2. Using *database_cross_section_plane_id, a cross section was set at 1/10 of the top of the pipe to extract the extrusion force between the pipe and the die during the reversal process. The total computation time was set to 0.03s. Using large-scale scaling technology to reduce CPU computation time, while keeping the mass increment within 5%. After relevant calculation control parameters were set, k file is imported into LsDyna 971 code for numerical calculation. The basic dimensions and material mechanical properties of low carbon steel pipes are shown in Table 1.

4. Discussions of simulation results

4.1 Influences of the die radius

During the simulation, it is assumed that the material does not tear. By comparing the results of initial inversion of plastic deformation under several smaller mold induction radius, it is found that the smaller the mold induction radius, the more difficult the inversion is. Fig. 6 shows the reverse defor-
information mode of the straight section of the pipe when it starts bending on the die A with different fillet radius. The inversion deformation performance of the pipe head under the radius of \( r = 9.0, 10.0 \) and 10.7mm is obviously better than that under the radius of \( r = 4.0, 5.2 \) and 8.0mm. When \( r = 4.0 \) and 5.4mm, the tubes were compressed and the tube head only expanded outward a little, without any indication of the inverting deformation. Through the comparison of simulation results, if the fillet radius of die A is between \( r = 4.0 \) and 8.0mm, the reverse deformation will not be completed. When \( r \geq 9.0 \)mm, the inverting deformation mode was gradually improved, showing a larger trend of natural inverting. When \( r = 10.0 \)mm, the inversion tendency of tube is more obvious. The buckling of tube when \( r = 10.7 \)mm did not occur under these simulation conditions.

Fig. 6 Inverting simulation results of the die A

Then, supplementary validation simulations were carried out for \( r = 10.9 \)mm and 11.1mm. There was little difference between \( r = 10.7 \)mm and \( r = 10.9 \)mm. However, when \( r = 11.1 \)mm, compared with \( r = 10.9 \)mm, the straight section of steel tube is obviously more prone to buckling. So you can see that as the radius of the rounded corner gets bigger and bigger. It is speculated that the best fillet radius of \( \Phi 60 \times 2 \)mm low carbon steel pipe die A is within the range of 10.7 \( \pm \) 0.1mm.

Fig. 7 shows the reverse deformation mode simulated by Mold B when the straight section of the steel pipe begins to bend. 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. Evidently, 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 tube head is still expanding circumferentially, the straight section begins to bend at the same time. This means that the outward phase reversal of the tube is going to be worse. Starting from \( r = 10.5 \)mm, the reverse deformation mode of the tube is obviously improved. By observing the tube head inversion deformation of \( r = 10.6 \)mm and 10.8mm, under the same simulation constraints, the degree of tube head inversion of \( r = 10.5 \)mm is less than that of \( r = 10.6 \)mm and 10.8mm. When \( r = 10.6 \)mm and 10.8mm, the successful trend of inversion is more obvious, and the two inversion deformation methods are basically the same.

In addition, the \( r = 11.2 \) and 11.5mm segments buckled earlier than the \( r = 10.8 \)mm segments, so the inverted pipe was more likely to fail. Therefore, it can be inferred that for Mold B, the optimal fillet radius \( R \) is also 10.7 \( \pm \) 0.1mm, which is consistent with the optim

Considering the mold manufacturing cost, a mold is simple and cost-effective. At the same time, a major advantage of mold B is that the deformation section of the inverted pipe head can be properly guided to extend upward a little, which is more convenient for the subsequent forming and welding of the inverted pipe head, and is convenient for the application of the inverted pipe.

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 inverteb pipe head can be appropriately guided to extend upward a little, which is more convenient for subsequent head shaping and welding installation for the inverteb application.
4.2 Axial squeezing forces in the inverting process

Fig. 8 shows the axial squeezing force curves of the tube against the die A with different fillet radii. In the early deformation stage of tube, the axial squeezing forces of $r=10.7$, 10.9 and 11.1mm are relatively small, about 15% lower than that of $r=9.0$ & 10.0mm. The v-shaped force drops in the curves are caused by the fact that the expanded tube head is extruded to the lowest point of the die upper surface and deformed to a horizontal state, while the forefront section suddenly loses the upward support. Then the squeezing force rises rapidly again as the forefront section goes into the upward inverting or comes across a block. As for the die working life, the smaller the axial squeezing force in the initial stage is, the more favorable it improves the durability of the die. Therefore, in order to finish inverting this kind of thin-walled tube, it is reasonable to set the fillet radius of the die A about 10.7mm.

Fig. 9 records the axial squeezing force curves in the inverting process of tube on the die B with different fillet radii. Compared with the die A, the peak force of the initial inverting deformation of the tube against the die B goes hand in hand under the same level, about 100kN. The axial squeezing force of the tube is relatively small when the fillet radius $r=10.5$mm and 11.0mm, so it can be seen that for the die B, the tube is more prone to invert when the die corner radius is within the range of 10.5-11.0mm.

![Fig.8 Axial squeezing force curves of the die A](image1)

![Fig.9 Axial squeezing force curves of the die B](image2)

5. The Mild Steel Invertube Manufacturing

In order to obtain the mild steel invertube with a better head shape, the die B with the rounder radius of 10.7mm was preferentially selected to manufacture. Then a cube of alloy steel was cut and machined by a numerical control machine in a small and local machining plant. The die B was finished as shown in Fig.10. Then the die B was fixed on a hydraulic pressure testing machine, with maximum pressure of 300kN. The mild steel thin-walled tubes were prepared with the outer diameter of 60mm, the wall thickness of 2.0mm and the length of 200mm. Then the thin-walled tube was put on the die B and its another end was compressed slowly by the top pressure head of the hydraulic pressure testing machine. The finished invertubes were finished after the tube head experienced the final shaping operation, as shown in Fig.11. It is can be seen that the straight line section is still kept straight, but the head shape is not ideal. The head surface is full of bumps and holes. Hence how to improve the shape of the invertube connecting head will be the main research objective next stage.
Sometimes, the inverting deformation of thin-walled tube will lead to failure. For example, thin-walled tubes will be over compressed due to the improper control of compression distance. Another reason is that small defects exist on the surface of the thin-walled tubes. The thin-walled mild steel tube inverting failure example is shown in Fig.12. It is obvious that the straight line section inflated outward, although the invertube head seems to be nice. So the key point to manufacture the mild steel invertube successfully is to control the compression distance accurately and keep the thin-walled tube straight from first to last.

6. Conclusions

In this paper, the optimal radius of the forming die is studied by taking the mild steel seamless thin-walled tube with 60mm outside diameter and 2.0mm wall thickness as the research object. The effect of different fillet radius on the plastic deformation of fillet of thin-walled tube was studied by using the fillet die of A and B section type. The results show that when the fillet radius is small, the tube head cannot be turned over normally. When the fillet radius of the die is about 10.7mm, the pipe head unfolds smoothly and turns over fully before the straight-line clip. The pipe head can often slide over the lowest point of the round surface of the die, but the total height of the pipe head turning upwards is relatively small. In addition, the optimal fillet radius calculated from formula (1) is significantly different from the theoretical value, and the predicted value of simulation is about twice of the theoretical value.

In addition, although the invertube manufacturing process and the finished invertubes verified the effectiveness of the optimal rounded radius of the die B, some flaws on the finished invertubes appeared on the tube head should be paid more concerns. These flaws need to be improved by some new modified measures further. Some operation suggestions mentioned above can guide a successful invertube manufacturing process using the mild steel thin-walled tube. The method used in this paper also provides the technical points for the design of the invertube die structure.

Acknowledgments

This Project was supported by the Natural Science Foundation of Zhejiang Province (LY20E050003), Key Public Project of Huzhou City (2018GZ05) & National Undergraduate Innovation and Entrepreneurship Training Program (2019G037) & Science and technology planning Project of Zhoushan City.

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