Influence of Semi Die Angle on the Forming Process of Ribbed Tube

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Abstract. Cladding tube is one of the key components in nuclear power reactor. In this paper, the forming process of a new cladding tube is investigated, namely ribbed tube. The influence of semi die angle on the forming process of ribbed tube is studied. Firstly, the strain-stress curves of 316L stainless steel (SS) at different strain rates are obtained. Based on the strain-stress curves, a modified Johnson-Cook constitutive model which ignore the influence of temperature are used, and the parameters of the modified model are determined. Then, the modified Johnson-Cook is used to establish the finite element (FE) model of ribbed tube drawing process, and two pass drawing process is adopted in this paper. Finally, the influence of semi die angle on the forming process (forming quality and drawing force) of ribbed tube is elucidated, and the credibility of the simulation is confirmed by comparing the simulation and experimental results. The results show that when the semi die angle less than 8°, all the formed ribbed tubes meet the requirement, but there are inner grooves appear at the inner wall, and the inner grooves cannot be avoided in the drawing process. Moreover, when the semi die angle is 8°, the inner grooves have smallest depth.

Keywords. Cold drawing, AISI 316L stainless steel, Johnson-Cook, ribbed tube, semi die angle.

1. Introduction

316L stainless steel (SS) is one of the most widely used austenitic stainless steels because of its excellent corrosion resistance, high-temperature mechanical properties and impact toughness [1]. Due to its excellent performance, 316L SS is often used in the manufacture of heat exchangers, and cladding tube. As one of the key components of the nuclear reactors, cladding tube plays a role in containing fission products and preventing the leakage of fission products, and is an isolation barrier between fuel and coolant [2]. In the past, the isolation between cladding tubes was achieved by welding steel wires outside the tube. Although this method is simple, because the spiral winding wire is fixed by spot welding, the spot welding part is easy to fall off under the long-term erosion of the high temperature and high pressure medium, resulting in isolation invalidate. To solve this problem, an integral structure of ribbed cladding tube is proposed. However, the manufacturing process and forming process of such special-shaped tubes still need further study.

For the forming process of tube parts, there are three methods: cold drawing, cold rolling and cold extrusion. Due to the high production efficiency, accurate product size and good surface quality, cold drawing process is widely used to manufacture tubes with small diameter, thin wall and special section.
Cold drawing process is a relatively mature process, which has been applied on a large scale since the beginning of the 20th century [4]. In recent decades, many scholars have conducted a lot of in-depth and detailed research on the drawing process and forming theory. Gattmah et al. [5] investigated the effects of semi die/plug angles on the drawing process, they pointed out that the die angle has a greater influence on the drawing force than the plug angle, and when the semi die angle is 12°, it has the minimum drawing force. Linardon et al. [6] studied the draw ability in the drawing process, and found that the friction coefficient is not a constant value, but is related to the pressure. At the same time, they figured out the reduction of area decreases with the increase of semi die angle. For the special-shaped tube forming process, Tang et al. [7] investigated the influence of process parameters on the forming process of micro copper tube with straight grooves, the results show that the groove depth and with of copper tube decreases with drawing diameter, and the thickness increases with the decrease of drawing diameter. Bella et al. [8] studied the forming process of steel tubes with straight internal rifling, and obtained suitable process parameters and optimal blank tube sizes for producing such special-shaped tubes.

Although a lot of research has been carried out on the cold drawing process of round tubes and special-shaped tubes, the influence of drawing process parameters on the forming results is also different due to the different cross-sectional shapes. Moreover, the forming process of ribbed tube as shown in figure 1 has not yet been studied. The specific dimensions of the ribbed tubes are as follows: out diameter (OD)=7mm, wall thickness (WT)=0.5mm, ribs height (RH)=0.5mm, fillet radius (R)<0.2mm, and the error fluctuation of all dimensions should be controlled within 0.05mm. Because the size of ribbed tube is very small and the precision is very high, it is difficult to manufacture. In this paper, based on finite element (FE) model, the cold drawing process of ribbed tube is investigated. Besides, to establish the FE model, the flow behaviour of 316L SS is obtained through uniaxial tensile experiments. Drawing dies with different semi die angles are used in this work to study the influence of semi die angle on the forming process of ribbed tubes.

![Figure 1. Cross-section of ribbed tube.](image_url)

2. Research Arrangements

2.1. Materials and Flow Behaviour

The materials used in this work are cold-rolled and annealed 316L SS, the initial structure is fully austenitic, and the structure contains partial annealing twins. To obtain the flow behaviour of 316L SS, uniaxial tensile tests are carried out and four strain rates (0.1 s⁻¹, 1 s⁻¹, 10 s⁻¹, 100 s⁻¹) are selected. The strain-stress curves of 316L SS with different strain rates are shown in figure 2. Many research figure out that the Johnson-Cook constitutive model can well describe the flow stress of materials during the drawing process [9, 10]. Therefore, a modified Johnson-Cook constitutive model which ignored the influence of temperature is used in this work:
\[
\sigma = (A + B \varepsilon_{eq}^n) [1 + C \ln \dot{\varepsilon}^0] \tag{1}
\]

where \( A, B, C, n \) are the yield strength, hardening modulus, strain rate sensitivity parameter and hardening coefficient, respectively. \( \varepsilon_{eq}, \dot{\varepsilon}_{eq}, \dot{\varepsilon}_0 \) are the equivalent effective strain, effective plastic strain rate and reference strain rate, respectively. Based on the strain-stress curves illustrated in figure 2, the parameters of the modified Johnson-Cook constitutive model are listed in table 1.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Stress-strain curves of 316L SS at different strain rates.}
\end{figure}

\begin{table}[h]
\centering
\caption{Parameters of modified Johnson-Cook constitutive model.}
\begin{tabular}{cccc}
\hline
\( A \) (MPa) & \( B \) (MPa\(^{-1}\)) & \( C \) & \( n \) & \( \dot{\varepsilon}_0 \) (s\(^{-1}\)) \\
\hline
200 & 1298 & 0.02 & 0.75 & 1 \\
\hline
\end{tabular}
\end{table}

2.2. Establish of Drawing Process FE Model

The FE model of drawing process is established in the software ABAQUS/EXPLICIT, as shown in figure 3 (a). This work adopts two pass drawing process, and without intermediate annealing process. Because of the symmetry of the model, in order to save time, 1/4 model is used, and the drawing dies are simplified too. Drawing dies and plugs are set as rigid body, while tube is set as deformed body. The mesh type of drawing dies is tetrahedron, and the mesh type of plugs and tube is hexahedron, and there are 8 elements in the thickness direction of the tube. During the cold drawing process, drawing dies and plugs are fixed, and the tube moves in the -z direction at a constant speed of 10 mm/s. The friction model used between the dies and tube, the plugs and the tube is Coulomb friction, and the friction coefficient is 0.07. Figure 3(b) gives the schematic diagram of the drawing die and plug, D is the inner diameter of drawing die, \( \alpha \) is the semi die angle, \( \beta \) is the semi plug angle, and \( \gamma \) is the angle of die grooves, R is the radius of the plug, respectively.
2.3. Experimental Arrangement

The drawing processes were completed on a laboratory drawing bench as shown in figure 4. Long mandrel, bolts and nuts are used to adjust the position of drawing plug. In the process of drawing, the tube is clamped by the collet and driven by an electric cylinder to complete the drawing experiment at a constant speed. Moreover, the specific parameters of the drawing tools are shown in table 2.

![Figure 4.](image-url)
Table 2 Parameters of drawing dies and plugs.

| Parameters (mm) | Die 1 | Die 2 | Plug 1 | Plug 2 |
|----------------|-------|-------|--------|--------|
| D              | 6.75  | 6     | -      | -      |
| β              | -     | -     | 15     | 15     |
| γ              | 10    | 10    | -      | -      |
| R              | -     | -     | 2.775  | 2.5    |

3. Results and Discussion

3.1. Effect of Semi Die Angle on Forming Results

Many scholars pointed out that in the drawing process, the semi die angle has an important impact on product quality. Therefore, this work will focus on the influence of the semi die angle on the forming quality of ribbed tube. Figure 5 gives the cross section of ribbed tube after drawing process at different semi die angle. The OD and WT of all ribbed tubes meet the requirements. When the semi die angle is less than 8 °, the ribs can fill the die grooves. When the half mold angle is greater than 8 °, the RH cannot meet the requirements. Besides, the stress level of ribbed tube is the same under all working conditions. Except that there is a large stress level at the bottom of ribs, the stress of other parts is uniform and similar. After the drawing process, inner grooves appear at the inner wall of ribbed tube. The reason is that the metal flows into the die groove, and the inner wall of the tube appears defects under the extrusion of the rounded corners of the drawing die.

![Figure 5. Cross section of ribbed tube at different semi die angle.](image)

When the semi die angle is 10°, the comparison between FE simulation and experimental results is shown in figure 6 (a). It can be seen that the simulation result is in good agreement with the experimental result, which proves that the simulation result is credible. Figure 6 (b) gives the formed ribbed tube, and obvious inner grooves can be observed on the inner wall of the ribbed tube. Such defects cannot be avoided in the drawing process of ribbed tube and can only be eliminated by other means. Therefore, further research is needed to eliminate the defects. However, at present, except for the inner grooves, the other dimensions of the ribbed tube meet the requirement.
Figure 6. (a) Comparison of FE simulation and experimental results (b) Formed ribbed tube.

Figure 7 illustrates the RH of ribbed tubes at different semi die angle. When the semi die angle is less than 8°, the RH of all ribbed tubes is 500μm, which meets the size requirement. However, when the semi die angle is larger than 8°, the RH decreases with the increase of semi die angle. Moreover, the evolution of groove depth shows in figure 7. As the semi die angle increases, the depth of the inner groove first increases and then decreases, and with a minimum value of 146 μm at 8°. Ribbed tubes under all working conditions have inner grooves, and this defect cannot be avoided during the drawing process of ribbed tubes. The optimal semi die angle is 8°, which not only meets the requirements of the RH, but also has the smallest inner groove depth. At this time, the rib bottom has the maximum stress value, indicating that increasing the extrusion force of the die fillet on the tube can effectively reduce the inner groove depth.

3.2. Effect of Semi Die Angle on Drawing Force
Since this paper focuses on the forming results of ribbed tube, and the length of tube is only related to the length of stable section of drawing force, and has no effect on other results, so the length of tube is set to 10 mm to reduce the time consumed in simulation. The evolution of drawing force during the drawing process is illustrated in figure 8. A small drawing force is conducive to the stability of the
drawing process. When the drawing force is too large, the tube may break in the drawing process. Due to the different semi die angle of the dies, the initial contact time between the tube and the die is different, but the drawing force trend of the first pass and the second pass is the same. Firstly, it increases to the stable drawing section with time, and the drawing force decreases gradually after the drawing is completed. Although the drawing force of 10° is the smallest, but the formed ribbed tube is not meet the requirements. The drawing die with a semi die angle of 8° not only has the best forming result, but also the drawing force is relatively small.

![Figure 8](image-url)

**Figure 8.** Evolution of drawing force during drawing with different dies.

Figure 9 gives the forming process of ribbed tube with 8° semi die angle drawing die. When t=1.5s, the tube begins to contact the die, the drawing force begins to increase, and reaches the maximum value at 2.5 s, enters the stable drawing stage. However, due to the small length of the tube, the duration of the stable stage is very short, and the first drawing ends at 3 s. Then the tube began to contact with the second pass die, entered the second pass drawing. Enter the stable drawing stage at 3.3 s, and finally complete the second drawing at 4.3 s.

![Figure 9](image-url)

**Figure 9.** Forming process of ribbed tube.
4. Conclusions

(1) A modified Johnson-Cook constitutive model ignoring the influence of temperature is used to describe the flow behavior of 316SS during drawing process, and the parameters are determined by strain-stress curves.

(2) When the semi die angle is less than 8°, the ribbed tubes meet the requirement. When the semi die angle is greater than 8°, the rib height cannot reach the required height. In addition, inner grooves are appeared in the inner wall of all formed ribbed tubes, and these defects cannot be avoided in the drawing process of ribbed tubes. With the increase of the semi die angle, the depth of the inner grooves first increases and then decreases, and with a minimum value of 146 μm at 8°.

(3) The drawing force of different drawing process with different dies is analyzed. When using the die with a semi die angle of 10°, the drawing force is the smallest. A small drawing force is conducive to the smooth drawing process, on the contrary, it will lead to the tube easy to fracture, especially the small-diameter thin-walled tubes.

(4) When the semi die angle is 8°, not only the formed ribbed tube has the smallest defects, but also has relatively small drawing force. Hence, for the drawing process of ribbed tube, the best semi die angle is 8°.

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