Numerical Simulation and Experimental Study on Rotary Cold Extrusion Forming of Screw Rod

Peiai Li, Baoyu Wang* and Jiapeng Wang
School of Mechanical Engineering, University of Science and Technology Beijing, No.30 Xueyuan Road, Haidian District, Beijing 10083, China. Email: bywang@ustb.edu.cn

Abstract. The rotary cold extrusion forming process is a plastic forming process with very low material loss, especially in the production of hollow screw rods with equal wall thickness. In this work, the rotary cold extrusion forming process of a hollow T2 copper screw rod with a wall thickness of 4 mm and solid T2 copper screw rod was verified by experimental method. The finite element simulation software Deform-3D was also used to simulate the rotary cold extrusion forming process of the screw rod. The effects of the die with different heights of the working belt and the different wall thickness of the billet on the eccentricity, extrusion force, and forming torque in the forming process of the screw rod were studied. The results show that it is feasible to process hollow and solid T2 copper screw rods with equal wall thickness by rotary cold extrusion. With the increase of die working belt height, the eccentricity of the screw rod becomes smaller and closer to the ideal eccentricity. With the increase of the wall thickness of the billet, the amplitude fluctuation range of the eccentricity of the screw rod gradually decreases. The higher the height of the die working belt, the greater the extrusion force and torque required in the extrusion process, and the more intense the change of torque. These results also provide theoretical guidance for the production practice and lightweight transformation of the screw pump rotor.

Keywords. Screw rod, equal wall thickness, rotary cold extrusion, numerical simulation, deform-3D.

1. Introduction
As a kind of liquid conveying equipment, the screw pump forms a sealing chamber through the intermeshing of internal screw rotors, which promotes the advance of liquid and realizes the liquid conveying. The rotor is the main component and has a three-dimensional (3D) spiral structure. At present, the screw pump rotor is usually formed by cutting metal bars with a special milling machine [1-3], and the material loss is about 50%. At the same time, there are also problems such as long processing time and low production efficiency.

Compared with the milling process, the extrusion forming screw pump rotor process has almost no material loss, and can also significantly improve the production efficiency. Many scholars have conducted a lot of research on the axisymmetric forward screw extrusion process [4-7]. Pater et al. [8] studied the extrusion forming process of twist drill by experiment and finite element (FE) method. Based on the neural network method, a mathematical model that can be used to describe the relationship between the geometric parameters of the die and the helix angle of the twist drill was established. The experiment proved that the split die was feasible for the extrusion forming of twist drill. Liu et al. [9-11] studied the forming process of large pitch and large helix angle aluminum alloy...
6063 outer helix surface by forward hot extrusion with FE simulation and experiment. The effects of process parameters such as extrusion temperature, extrusion speed, extrusion ratio and billet length on the extrusion quality of external spiral surface were analyzed. Zhu et al. [12] used the FE simulation method to study the extrusion forming process of spiral circular tube and spiral elliptical tube, and determined the forming scheme of spiral elliptical tube by one-step extrusion with external die method. They also analyzed and discussed the influence of energy change, forming force, stress distribution and friction factor on the forming quality of spiral elliptical tube. At present, there are few reports on the extrusion process of non-axisymmetric solid and equal thickness screw rod.

In this paper, numerical simulation method was used to study the effects of the different working belt heights of the die and the different wall thickness of the billet on eccentricity, extrusion force, and forming torque in the process of screw rod rotary cold extrusion. At the same time, the feasibility of rotary cold extrusion forming hollow screw rod with equal wall thickness and solid screw rod process was verified by experimental method.

2. FE Simulation and Experiment

2.1. FE Simulation

The rotary cold extrusion process of the screw rod was studied by using the finite element model (FEM) shown in figure 1(a). Using 3D modeling software Pro/E, 3D models of billet, extrusion cylinder, push rod and die were established, and they were imported into Deform-3D FE software. In the FEM, the push rod moves along the axial direction according to the green arrow, and promotes the billet to move in the direction of the die. The die rotates around the axis of the billet at a constant speed according to the red arrow (The rotation direction of the die is opposite to the spiral upward direction of the screw rod). The billets are T2 solid copper rods and hollow copper tubes with equal wall thickness (Wall thickness $\delta = 2$ mm, 4 mm, 6 mm). Their diameters and lengths are 15 mm and 100 mm, respectively. This is consistent with the material and geometrical parameters of the copper rods and tubes used in the experimental study. The number of mesh elements of the billet is $7 \times 10^4$, and the mesh element is tetrahedral. The geometric dimensions of screw rod parts are shown in figure 1(b). The cross-section is made perpendicular to the axis in the direction of the axis of the screw rod, and the cross-section profile is a circle. The distance between the center of the circle and the axis of the screw rod is the eccentricity, expressed as $e$. This value is constant, different specifications of screw rod parts corresponding to different $e$ values. The eccentricity of the part used in this paper is $e=3$ mm.

Figure 1. FEM and geometric dimension for rotary cold extrusion forming of screw rod: (a) FEM, (b) Geometric dimension of the screw rod (mm).
The rotational angular velocity of the die and the moving velocity of the push rod in the rotary extrusion forming process of the screw rod should satisfy the following equation:

\[
\omega = \frac{2\pi V}{\sqrt{S^2 + (\pi D)^2}}
\]  

(1)

where \( \omega \) is the angular velocity of the die rotation, \( V \) is the moving speed of the push rod, \( S \) is the pitch, \( D \) is the diameter of the projection circle of the moving trajectory line of the center point of the screw rod in the horizontal plane, the value is \( 2e \). The main parameters set in the FE simulation are listed in Table 1.

### Table 1. Simulation parameters for screw rod rotary extrusion.

| Parameters                                           | Value |
|------------------------------------------------------|-------|
| Temperature of the billet (°C)                       | 20    |
| Environmental temperature (°C)                       | 20    |
| Friction factor between billet and extrusion cylinder | 0.2   |
| Friction factor between billet and push rod          | 0.2   |
| Rotational angular velocity of die (rad/s)            | 1.57  |
| Velocity of push rod (mm/s)                          | 10    |

It is assumed that the die is not deformed and is regarded as a rigid body. The shape of the curved cavity of the working belt is consistent with that of the outer surface of the ideal screw rod. In order to study the influence of different working belt heights on the forming quality of screw rods, dies with six different working belt heights were selected for simulation analysis in this paper, and their detailed geometric parameters are shown in Figure 2.

**Figure 2.** Geometrical parameters of die with different working belt heights: (a) 6.66 mm, (b) 13.33 mm, (c) 20 mm, (d) 26.66 mm, (e) 33.32 mm, (f) 40 mm.
In this paper, on the basis of single factor variables, the effects of different working belt heights and different billet thickness on the eccentricity, forming force, and torque of the rotary cold extrusion screw process were studied. The simulation conditions are shown in Table 2.

| Variable                               | Working condition          |
|----------------------------------------|-----------------------------|
| Working belt height (mm)               | 6.66 13.33 20.00 26.66 33.32 40.00 |
| Solid bar or wall thickness of tube (mm)| Solid Solid Solid/2/4/6 Solid Solid |

2.2. Rotary Cold Extrusion Experiment
In this paper, the screw rod rotary cold extrusion process was verified by experiments, and the FE results were compared with the experimental results. The experimental equipment and die (working belt heights: h = 6.66 mm and h = 20 mm) are shown in Figure 3. The extruded billet is solid T2 copper rod and copper tube with 4 mm wall thickness, and their lengths and diameters are 100 mm and 15 mm, respectively. Before the experiment, the lubricant (MoS2) was applied to the contact surface of the die and the billet to reduce the friction factor between the billet and the die.

Figure 3. Test equipment and die: (a) Structure of rotary extrusion equipment and die, (b) Rotary extrusion equipment.

The billet was clamped by the chuck during the experiment, and the part of the billet not clamped by the chuck was placed in the extrusion cylinder. The chuck was clamped by No.1 constant torque spanner and rotates clockwise around the axis (Red arrow in Figure 3(b)). The chuck rotates with the No.1 constant torque spanner and the billet rotates. The rotation direction of the billet is opposite to the rotation direction of the die in the FE simulation process. The guide screw was clamped and rotated around the axis by No.2 constant torque spanner, and its rotation direction (Yellow arrow in Figure 3(b)) was opposite to that of No.1 constant torque spanner. The guide screw also moves along the axis while rotating. The guide screw drives the push rod, and the push rod drives the billet to move along the axis direction to the position of the die. The billet was pushed into the die by the push rod. The billet was extruded in the die and finally formed a screw rod.

3. Results and Discussion

3.1. FE Simulation Verification of Rotary Cold Extrusion
Figures 4 (a) and 4(c) show the samples obtained by rotary cold extrusion of hollow T2 copper tube with a die of h = 20 mm and solid T2 copper rod with a die of h = 6.66 mm. The radial deviations of the profile surface of the experimental sample and the numerical simulation sample are shown in Figures 4(b) and 4(d).
In this paper, a high-precision 3D scanner was used to scan the entity of the sample formed by die extrusion with different working belt heights, and the geometric data were obtained. Then the FEM was compared with the geometric dimensions of the extruded parts obtained by previous scanning using Geomagic Qualify software. Figure 4 is the comparison of the radial geometric dimension of the profile surface of the FEM and the experimental sample. The different colors in the cloud chart represent the radial distance between the FEM and the experimental results at this point. The positive values indicate that the radial dimensions of the FE simulation results are larger than the experimental results, or that the profile surface of FEM is outside the profile surface of the experimental results. The negative values indicate that the radial dimension of the simulated result is smaller than the experimental result, that is, the profile surface of FEM is inside the profile surface of the experimental result. The greater the absolute value of the numerical value, the greater the radial distance between the FE results and the experimental results.

As shown in figures 4(b) and (d), the radial difference distributions of the maximum and minimum diameters of the extruded parts corresponding to these two FE simulation results are in the range of $(3.545 \sim 3.545 \text{ mm})$ and $(4.936 \sim 4.936 \text{ mm})$, respectively. There is a certain deviation between the FE simulation results and the geometric dimension of the experimental sample, but the overall deviation is not large. This is due to the uneven movement speed of the push rod and rotation speed of the billet during the experiment. In addition, this further verifies the feasibility of forming a screw rod by the rotary cold extrusion process.

3.2. Analysis on the Influence of Working Belt Height and Billet Wall Thickness on Eccentricity

Eccentricity is an important evaluation index to evaluate the forming quality of parts. The center point of the circular plane at the top of the copper rod and tube shown in figure 5 was chosen as the feature tracking point for analysis. The ideal feature tracking point is projected on the XOY plane as a circular trajectory with a constant radius (red circle) during the forming process from rod to screw rod. The trajectory variation of tracking points in the actual formation process needs to be understood in further research.
Firstly, the coordinates of the tracking points at different moments in the forming process of the screw rod were counted. Secondly, the distance (eccentricity) between the coordinates of the tracking points and axis (z-axis) of the ideal screw rod was calculated.

Figure 6(a) shows the change of eccentricity in the process of forming solid screw rods by the die with different working belt heights. Figure 6(b) shows the variation of eccentricity of hollow screw rods with different wall thicknesses in the forming process. In figures 6(a) and 6(b), the dotted line is the eccentricity of the ideal screw rod, and the height of the line is a constant value. The curve of eccentricity changing with time in the forming process of screw rod fluctuates, because the rotation axis of screw rod does not completely coincide with the ideal screw rod axis. It can be seen from figure 6(a) that at the initial stage of the forming process (0 ~ 2s). The billet begins to enter the die cavity under the axial thrust of the push rod. In the forming process of the billets using the dies with different working belt heights, the eccentricity changes of their tracking points are basically the same, which first decreases and then increases, and coincides with the ideal eccentricity at t = 2s. With the continuous extrusion work, the eccentricity of the screw rod formed by the die with the working belt heights of h = 6.66 mm and h = 13.33 mm gradually increases. The eccentricity of the screw rod formed by the die with the working belt height of h = 6.66 mm reaches 18 mm after the extrusion is completed. The maximum eccentricity of the screw rod formed by the die with the working belt height of h = 13.33 mm is 10.5 mm. The eccentricity of the screw rod formed by the extrusion of these two dies is much larger than that of the screw rod formed by other dies. The trajectory of the tracking point represents the motion of all points distributed along the axial direction below that point. After the extrusion, the eccentricity of the center point of the horizontal cross-sectional circles of the screw rod formed by the dies with h = 6.66 mm and h = 13.33 mm is larger at the position far from the push rod, and smaller at the position near the push rod. Therefore, the screw rod after forming appeared with different degrees of inclination. After t = 2 s, the eccentricity of the tracking point of the screw rods formed by the die with h = 20.00 mm, 26.66 mm, 33.32 mm, and 40.00 mm fluctuates periodically around 3. The eccentricity of the tracking point of the screw rods formed by the four different dies is changed to 3 mm every 2 s. The change trend of the eccentricity of the tracking point is basically the same, only the amplitude of the fluctuation is different. In the forming process of the die with h = 20 mm, the fluctuation amplitude of eccentricity is relatively large. The maximum value appeared at 9 s, and the minimum eccentricity almost coincides with the axis of the screw rod. With the increase of working belt height of die, the fluctuation amplitude of eccentricity decreases gradually. The maximum eccentricity of the screw rod obtained by extrusion with the die h = 40 mm is 3.5 mm, and the minimum is 2.5 mm.
Figure 6. Variation of screw rod eccentricity: (a) Dies with different working belt heights, (b) Billets with different wall thicknesses.

Figure 6(b) shows the variation of the eccentricity of three hollow copper tubes with different wall thicknesses in the screw extrusion process. When the wall thickness is 2 mm, the eccentricity of the billet does not change before \( t = 1.4 \) s, which is due to upsetting at the bottom of the billet at the position of contact with the push rod. With the continuous extrusion work, the eccentricity of the hollow screw rod increases gradually, and the maximum eccentricity reaches 6.5 mm. The screw rod also appeared inclined. When the wall thickness is 4 mm, the upsetting phenomenon disappears. However, the amplitude variation of eccentricity is less than that of the wall thickness of 2 mm. The hollow screw rod also has a certain degree of inclination, but the degree of inclination is smaller than that when the wall thickness is 2 mm. When the wall thickness is 6 mm, the variation curve of eccentricity with time is basically consistent with the curve of solid screw rod formed by the die with \( h = 20.00 \) mm, and the variation range of eccentricity is basically the same. The variation range of the eccentricity amplitude of the hollow screw rod with a wall thickness of 6 mm is smaller than that of the other two hollow screw rods with different wall thicknesses.

3.3. Analysis of the Effect of Working Belt Height on Axial Force and Torque

The axial force and torque of the die with different heights of working belt in the forming process of screw rod are shown in figure 7. It can be seen that as the height of the working belt of the die increases during the forming of the screw rod, the steady-state axial force to which the die is subjected also increases. The minimum steady-state axial force is 12.3 KN, and the maximum steady-state axial force is 34.7 KN, which is 2.8 times of the minimum steady-state axial force. This may be because with the increase of the working belt height, the contact area between the billet and the die cavity surface is also larger, and the friction force is also larger, and the axial force required to overcome the friction force is also larger. With the increase of the working belt height of the die, the torque of the die generally shows an increasing trend, but when \( h = 13.33 \) mm, the torque is lower than that when \( h = 6.66 \) mm. The torque applied to the die at \( h = 40 \) mm is also lower than that at \( h = 33.32 \) mm. Therefore, in the actual forming of the screw rod, the axial force and torque to which the die is subjected need to be taken into account in order to select a suitable working height for the die.
Figure 7. Numerical simulation results for the axial force of the push rod and the torque of the die (a) Axial force (b) Torque.

4. Conclusions
(1) After solid copper rod and hollow copper rod with \( \delta = 4 \) mm were extruded by rotary cold extrusion forming test, solid and hollow screw rods were obtained, respectively, indicating that it is feasible to form solid and hollow screw rods by rotary cold extrusion process.

(2) With the increase of die working belt height, the eccentricity of the screw rod becomes smaller and closer to the ideal eccentricity. With the increase of the wall thickness of the billet, the amplitude fluctuation range of the eccentricity of the screw rod decreases gradually.

(3) The higher the working belt is, the greater the axial force and torque the die needs to bear in the extrusion process. The torque changes more intensely.

Acknowledgments
This work is funded by the National Natural Science Foundation of China (Grant No. 51875036).

References
[1] Liu X Z, Liu M K, Chai X T, Wang L, Wang Y Q and Gan S Y 2020 Chin. J. Vac. Sci. Technol. 40 169-173
[2] Jiao M D 2012 Technology Innovation and Application 67
[3] Wei G J and Jin Y S 2005 Fluid Mach. 33 38-40
[4] Wu Y J, He J L, Chen Z, Zhang Z M, Li G J and Xue Y 2019 Forg. Stamping Technol. 33 65-71
[5] Kuboki T, Ishikawa M, Kajikawa S and Murata M 2018 CIRP Annals - Manuf. Technol. 67 305-308
[6] Jaechan C, Haeyong C and Hyukhong K 1994 J. Mater. Process. Technol. 44 35-53
[7] Hwang Y M and Chang C N 2014 Procedia Eng. 81 2249-54
[8] Bulzaka T, Paterb Z, Tomczaka J and Majerskib K 2019 J. Manuf. Process. 45 123-137
[9] Liu H G, Zhao B B and Xia F 2017 Forg. Stamping Technol. 42 169-174
[10] Liu H G, Xia F and Zhao B B 2018 Hot Working Technology 47 136-140
[11] Xia F, Li H, Liu H G, Zhao B B, Zhang Z Q, Lu D H and Chen J Q 2019 J. Cent. South Univ. 26 2307-17
[12] Zhu H Y and Yang H B 2008 Shanghai Met. 30 08-12