Simulation for drawing process of core filled tube

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Abstract. In this study, finite element method (FEM) was adopted to analyze the drawing process of the core filled tube (CORFT), and wall thickness and relative density of the core material were obtained. The prediction results of the FEM were compared with experimental results, revealing good agreement between them. Both the simulations and the experiments showed the existence of an ultimate relative density of the core material during the drawing of the CORFT. The influences of the process parameters on the ultimate relative density of the core material were determined using the FEM.

1. Introduction
Energy saving[1] and solid waste disposal[2] are two key problems in iron and steel industry. Core filled tube (CORFT)[3,4], using blast furnace slag (BFS) which is typical solid waste in iron and steel industry, has typical characteristics of energy saving and emission reduction. CORFTs, fabricated by using the process in literatures[3, 4], were shown in Figure 1(a). The CORFTs can be used as substitutions of steel bars and steel tubes when used in road fence, shown in Figure 1(b).

Some researches had been done in composite rod, like high-temperature superconducting wire/tape[5] and canning material[6,7]. Lu et al[8] simulated the drawing process of Bi-2223/Ag wires, and they obtained products with well distributed core material. Pandheeradi et al[9] simulated the rolling process of high-temperature superconducting tape, and they predicted the shape variation of the workpiece during the rolling process.
As for CORFT, the deformation law during the drawing process has not been reported. In this paper, firstly, the drawing process of the CORFT was simulated, and the change law of the wall thickness and the relative core density of the core material were obtained. Then, 6 passes of drawing experiments for the CORFT were conducted in order to verify the correctness of the finite element model. After that, the flow rule and relative density distribution of the core material were analyzed by using the previous finite element model. Finally, the influences of several process parameters on the ultimate relative density of the core material were analyzed.

2. Simulation for the drawing process of the CORFT

2.1. Establishment of the finite element model

During the drawing process of the CORFT, axisymmetric finite element model (shown in Figure 2) was adopted, because the drawing die, packed billet and force state are all axisymmetric. As shown in Figure 2, the die was fixed and both the steel tube and the BFS can move freely along the axis of rotation.

![Finite element model for the drawing process of the CORFT.](image)

Table 1. Diameters of outlet areas for the six dies.

| Serial number of passes | Diameter (mm) |
|------------------------|--------------|
| 1                      | 23.08        |
| 2                      | 21.13        |
| 3                      | 18.99        |
| 4                      | 18           |
| 5                      | 17.05        |
| 6                      | 16.04        |

Abaqus/Explicit 2017 was used to simulate the 6 drawing passes of the CORFT. The die angles \( \alpha \) were all 10°, the lengths of the sizing areas \( l_s \) were all 8.5 mm, and the exit diameters \( D_a \) of the dies were shown in Table 1. The style and size for the element of the die were CAX4 and 0.3 mm, respectively. The diameter, wall thickness and length of the outer steel tube were 25 mm, 1 mm and 150 mm, respectively. And the style and size for the element of the die were CAX4R and 0.2 mm, respectively. The diameter and length of the inner BFS were 23 mm and 149 mm, respectively. And the style and size for the element of the die were CAX4R and 0.4 mm, respectively. Von-Mises and Modified Drucker-Prager Cap model were adopted as the constitutive models of the steel tube and the BFS, respectively. Both the contact pairs of the surface between the die and the steel tube and the surface between the steel tube and the BFS were adopted as Coulomb friction law, and the friction coefficients were 0.15.
2.2. Verification experiments procedure
When preparing the CORFTs, the inner and outer oil stains on each tube were first removed with anhydrous ethanol. Then, one end was welded to a core rod. Next, the inside of the tube was filled with the prepared BFS. Finally, the CORFT products were manufactured using a six-pass drawing process. A CMT5105 # Electromechanical Universal Testing Machine was used to provide the drawing force. The drawing speed was 250 mm/min. The CORFT and HT drawing experiments were repeated three times in order to obtain reliable results.

The sizes of the six drawing dies were measured. The die angles $\alpha$ were all 10°. The lengths of the sizing areas were all 8.5 mm, and the diameters of the sizing areas are listed in Table 1.

3. Results and discussion

3.1. Verification of the finite element model
As shown in Figure 3(a), during the drawing process of the CORFT, both the numerical and experimental results of the wall thickness increased first and then decreased, and the error ratio between them was in range of -2.2% and 0.3%. As shown in Figure 3(b), during the drawing process of the CORFT, both the relative density $z$ of the core material for the numerical and experimental results increased first and then remained unchanged (or namely the core material has an ultimate relative density $z_U$), and the error ratio between them was in range of -1.1% and +1.2%. The $z_U$ of the simulation and the experiment were 0.835 and 0.834, respectively, the error ratio was 0.1%. Figure 3 validated the correctness of the finite element model in predicting the parameters $s$ and $z$ during the drawing process of the CORFT.

![Figure 3. Comparison between FEM and experimental results (a) wall thickness $s$; (b) relative core density $z$.](image)

3.2. Research on the basic deformation law
The relationship between the relative density of the core material and the axial coordination after the 1-th drawing pass was shown in Figure 4. It can be shown that according to the time order, the drawing process of the CORFT can be divided into 4 stages. They were initial drawing stage (area a in Figure 4), stable drawing stage (area b in Figure 4), near final stage (area c in Figure 4) and final stage (area d in Figure 4). During the drawing process of the CORFT, the $z$ continuously increased at the initial stage and the increasing speed continuously decreased, the $z$ remained invariant at the stable stage, the $z$ increased at the near final stage, and the $z$ rapidly decreased at the final stage.
In order to analyze the cause of the 4 drawing stages, the axial velocity $v$ and the relative density $z$ of the core material at the 4 drawing stages of the first drawing pass were drew, shown in Figure 5. It can be shown from the above figure that during the 4 drawing stages, the axial velocity of the core material is always lower than that of the outer steel tube, or namely, the core material flows into the undeformed area, thus the $z$ tends to decrease. At the same time, the $z$ tends to increase because of the decrease of the core material diameter. Thus, among the 4 drawing stages, the deformation law of the $z$ depends on the velocity of the core material flow into the undeformed area and the drawing reduction.

During the first drawing pass of the CORFT, the $z$ is determined to the velocity of the core material flows into the undeformed area because that the drawing reduction remains unchanged during the 4 drawing stages. At the initial drawing stage, with the drawing proceeds, the velocity of the core material flows into the undeformed area is small because of the small $z$, thus, the $z$ increases. With the increases of the $z$, the increasing speed decreases because that the velocity of the core material flows into the undeformed area becomes smaller and smaller. When the increasing speed of the $z$ decreases into 0, the drawing process goes into stable stage. At this time, the change of the $z$ caused by the above two factors cancels each other out, thus, the $z$ remains unchanged. At the near end stage, the flow resistance of the core material increases because of the resist of the weld joint at the end of the steel tube. Thus, the $z$ increases with the proceed of the drawing process. At the end stage, the weld joint at
the end of the steel tube bends and bulges, the flow resistance of the BFS decreases, thus the \( z \) decreases dramatically with the proceed of the drawing process.

In order to further analyze the flow law of the BFS during the drawing process of the CORFT, the distribution of the axial velocity of the BFS and the relative density of the core material at the stable drawing stage is plotted, shown in Figure 6. As shown in Figure 6(a), at the stable drawing stage, in a same section, the velocity of the core material flows into the undeformed area distributes nonuniform, the velocity of the BFS flows into the undeformed area at point a is bigger than that at point b, or namely, the front of the BFS flowing into the undeformed area forms an ellipsoid. This is because that at the stable drawing process, the core material flows into the undeformed area (due to the compression effect), but at the same time, the flow resistance of the BFS near the inner surface of the steel tube is bigger (due to the friction between the BFS and the steel tube), finally, the front of the BFS flowing into the undeformed area forms an ellipsoid. Similarly, the core material has an ellipsoid area where the \( z \) is higher than the other undeformed area, as shown in Figure 6(b), or namely, the \( z \) at point c is bigger than that at point d. Meanwhile, as shown in Figure 6(b), at stable drawing stage, the \( z \) at the center of the BFS (point e) is lower than that at the outer of the BFS (point f). This is because that the flow of the core material at point e is blocked due to the friction.

![Figure 6](image_url)

**Figure 6.** Distribution of axial velocity and relative density for stable drawing stage (a) axial velocity; (b) relative core density.

The flattening resistance of the CORFT is better with higher parameter \( z_U \) because of the higher holding force on the inner surface of the steel tube provided by the BFS. As shown in Figure 7, the \( z \) firstly increases with the decrease of the \( D \) with different process parameters, and then remains invariant, and the parameters have impact on the \( z_U \).

As shown in Figure 7(a), the \( z_U \) decreases slightly with the increase of the coefficient of friction \( f \). During the drawing process of the CORFT, when the \( z \) equals to the \( z_U \), the elongation trend increases with the increase of the \( f \); thus the \( z_U \) decreases with the increase of the \( f \). As shown in Figure 7(b), the \( z_U \) decreases with the increase of the die angle \( \alpha \). During the drawing process of the CORFT, when the \( z \) equals to the \( z_U \), the flow velocity of the core material along the axial direction increases with the increase of the \( \alpha \); thus the \( z_U \) increases with the increase of the \( \alpha \). As shown in Figure 7(c), the \( z_U \) increases with the decrease of the ratio between the back tension and the yield strength of the steel tube \( b_p \). During the drawing process of the CORFT, when the \( z \) equals to the \( z_U \), the axial stress \( \sigma_x \) of the steel tube decreases with the decrease of the \( b_p \) (or namely, the elongation trend decreases), thus the \( z_U \) increases with the decrease of the \( b_p \). As shown in Figure 7(d), the \( z_U \) increases with the increase of the yield strength of the steel tube \( \sigma_s \). At the initial drawing process of the CORFT, the stress on the inner surface of the steel tube \( \sigma_{in} \) provided by the BFS is small and can be neglected. When the \( z \) equals to the \( z_U \), with the increases of the \( \sigma_s \), the parameter \( \sigma_{in}/\sigma_s \) decreases, or namely the elongation trend decreases, thus the \( z_U \) increases with the increase of the \( \sigma_s \).
Figure 7. Effect of parameters on relative density $z$ (a) friction coefficient $f$; (b) angle of the die $\alpha$; (c) ratio of the back force and yield strength of the steel tube $b_p$; (d) yield strength of the steel tube $\sigma_s$.

4. Conclusions
This study has the following three conclusions:

(1) A finite element model (FEM) for 6 passes of drawing process for the core filled tube (CORFT) was built, and wall thickness $s$, relative density $z$ of the core material and ultimate relative density $z_U$ of the core material were obtained. The error ratio of the $s$ was in range of -2.2% and 0.3%, the error ratio of the $z$ was in range of -1.1% and 1.2%, and the FEM and experimental results of the $z_U$ were 0.835 and 0.834, respectively, which validated the correctness of the FEM in predicting the drawing process of the CORFT.

(2) According to the results of the FEM, the core material flowed into the undeformed area during the drawing process of the CORFT. According to the distribution of the flow velocity and the relative density of the core material, the drawing process can be divided into 4 stages (initial drawing stage, stable drawing stage, near final stage and final stage).

(3) The influences of several parameters on the $z_U$ were analyzed, the parameters included friction coefficient $f$, angle of the die $\alpha$, ratio of the back force and yield strength of the steel tube $b_p$, and yield strength of the steel tube $\sigma_s$.

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