Deformation characteristics in 3D free-bending forming of complex spiral tubes

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Abstract. Free-bending is a novel bending technology suitable for tube and profile bending. It can achieve accurate bending of tubes or profiles with different bending radii without die. In current study, a new theoretical analysis of a spiral tube formed by 3D free-bending is proposed to reveal the relationship between the spiral tube and the parameters of free-bending forming technology. The results obtained from the proposed theoretical analysis were compared with those achieved from FE modelling and experimentation. The maximum error of forming was less than 7%, which verified the accuracy and the reliability of the proposed theoretical model. The forming limits of the spiral tubes based on 3D free-bending were explored. It was noticed that the spiral diameter was mainly influenced by the eccentricity and the distance between the center of the bending die and the front end of the guide mechanism in the Z-direction (distance A). Furthermore, the spiral diameter is inversely proportional to the eccentricity, and directly proportional to the distance A. In addition, the screw pitch is mainly influenced, and directly proportional to the spiral diameter and the single spiral circle swing angle of the spherical bearing.

Keywords: Free-bending; Trajectory of bending die; Spiral tubes; Theoretical analysis; forming limit

1. Introduction
Spiral tubes are 3D spiral structures mainly used to transfer oil and gas, and play an important role in petroleum, chemical, and power industries [1-3]. Spiral tubes are usually used as buffer tubes in the fluid tube and are generally placed in the front section of a pressure gauge to reduce the impact force on a pipeline conveying fluid and facilitate the calculation of normal pipeline pressure [4]. Therefore, it is of great significance to study the forming of spiral tubes. The forming of a spiral tube involves space-bending, which is difficult to perform. At present, spiral tubes are mainly formed through traditional bending methods, including roll bending [5], and numerical control bending [6]. Wang [7] studied and
analyzed the roll bending forming process of spiral tubes, established a theoretical model of space bending forming, and put forward the influence law of roll bending on the forming quality of spiral tubes. Jing et al. [8] investigated the control of winding process of thin wall spiral tubes using an elastic-plastic finite element method, and analyzed the location and magnitude of the maximum tensile stress and maximum compressive stress, thereby providing a theoretical base for the control of working forming course of thin wall spiral tubes. Cui et al. [9] designed and investigated a spiral tube structure working under high temperature and high-pressure loads. A CAE method was used to calculate and analyze the performance of this spiral structure under working conditions. In addition, a number of studies have explored the forming limit of tube bending. Daxin et al. [10] established a relationship between the material hardening index and the minimum relative bending radius. The calculation formula of the minimum relative bending radius of the tube was derived according to the theory of concentrated instability and dispersion instability. Hu et al. [11] developed a computer simulation system based on stress state and deformation analysis of tube bending, using local induction heating with small bending radius. Langenbrunner et al. [12] investigated a method which tube is filled by sand before bending to avoid the wrinkling in thin-walled tubes in bending process. This method can effectively increase the forming limit of tube bending, but it cannot be used in the forming process of complex tube fittings. Hasanpour et al. [13] studied the influence of anisotropy on the ellipsis, thickness and wrinkle of tube by finite element method, and explored the forming limit of tube. The newly developed free bending process has proved to have many advantages. Free-bending is a continuous bending and die-less forming method [14-17]. Compared to traditional bending, it has the advantage to be a low-cost continuous forming method [18, 19]. In general, it has been demonstrated that the theory of bend forming of spiral tubes is not perfect, and especially bend forming based on the 3D free-bending technology has not been investigated. Moreover, the forming limit of spiral tubes has been seldom studied.

In this study, the 3D free-bending technology was used to form spiral tubes. However, the free-bending technology is still in the research stage and its theory is far from perfect. Therefore, in the present study, a theoretical model of spiral bending based on the free-bending technology is presented, and the relationship between pitch, diameter, and free-bending parameters is revealed. At the same time, the accuracy of the theoretical model was validated by simulations and experiments, and the forming limit was explored based on the theoretical model.

2. Finite element modelling

Firstly, a three-dimensional model of the free-bending system was designed, and then it was imported into the finite element software ABAQUS (Fig. 1).

![Figure 1. Finite element model](image)

The analysis step was set as dynamic explicit, the interaction was defined as universal contact, and the global friction coefficient between the tube and die was set to 0.2. Moreover, the diameter of the tube was 15 mm, and the thickness of the wall was 1 mm. 6061-T6 aluminium was used as the material model of the tube, and YG8 cemented carbide was used as the bending die material. The specific parameters are presented in Table 1.
Table 1 Materials’ mechanical properties at room temperature

| Materials | Poisson's Ratio | Young’s Modulus $Y$ (GPa) | Tensile Strength $R_m$ (MPa) | Density $\rho$ (g/cm$^3$) |
|-----------|----------------|-------------------------|---------------------------|---------------------|
| 6061-T6   | 0.3            | 80.7                    | 260                       | 2.7                 |
| Aluminum  |                |                         |                           |                     |
| YG8       | 0.3            | 71                      | *                         | 14.5                |

As it can be seen in Fig. 2, the simulation results are consistent with the theoretical analysis. More specifically, in Fig. 2(a), it can be observed that there is stress concentration in the position where the bending die swinging. On the lateral bend side of the spiral tube, there is tensile stress concentration at the swinging position. On the contrary, at the inner bend side of the spiral tube, compressive stress concentration is developed.

Figure 2. Spiral free bending forming simulation: (a) Stress cloud; (b) Wall thickness cloud

Under the action of stress, the wall thickness distribution in the spiral tube also has a certain influence at the position of bending die swinging. As it can be seen from Fig. 2(b), the thinning rate of the outer bend side is greater and the thickening rate of the inner bend side is greater in the swinging position of the bending die. The results of the simulation were basically consistent with the theoretical analysis.

Figure 3. Simulated wall thickness distribution of spiral tubes
The stress state has a significant effect on the wall thickness distribution. As it can be seen from Fig. 3, there is an uneven wall thickness distribution in the spiral tubes. At the position where the bending die swinging, the maximum thickening of the inner side wall was 1.4% higher than that of the other parts, and the maximum thinning of the lateral side wall was 1.2% higher than that of the other parts. However, in general, the thickening and thinning of the wall at the swinging position of the bending die appeared to have little effect on the overall forming quality of the spiral tubes.

3. Experiments of free-bending forming

In this study, based on the forming process of spiral tubes, free-bending forming experiments were carried out (Fig. 4). In these experiments, a three-axis free-bending forming equipment was used, and the required spiral tube parts were formed. According to the theoretical analysis and simulation results, the swinging angles of the bending die will be produced by a large force, which has a certain influence on the wall thickness distribution of the tube. As it can be seen in Fig. 5, the wall thickness distribution resulted from the spiral bending experiments was basically in line with the theoretical and simulation results. At the swinging position of the bending die, the maximum thickening of the inner wall was 1.5% higher than that of the other parts, and the maximum thinning of the outer wall was 0.8% higher than that of the other parts. However, these changes have no significant effect on the forming quality of the final spiral tubes.

Figure 4. Bending forming experiments: (a) Forming equipment; (b) Free bending forming of spiral tubes.

Figure 5. Experimental wall thickness distribution of spiral tubes
After comparing the spiral tube geometric model, the simulation results, and the experimental results, it was found that the overall forming effect was good with no apparent forming defects (Fig. 6). In Table 2, it can be seen that the maximum error of the spiral diameter of the simulation and experiment does not exceed 6.5%, and the maximum error of the spiral pitch does not exceed 7% compared to the three-dimensional model. As it can be observed, the reliability and accuracy of the theoretical process was strongly validated by the computational and experimental results.

| Parameters | Spiral tube model | Simulation result | Experimental result |
|------------|-------------------|-------------------|--------------------|
| Spiral diameter D | 130                | 138               | 136                |
| Screw pitch S      | 60                 | 61                | 64                 |

In order to further verify the reliability of the theoretical process, a more complex multi-loop spiral free-bending forming was performed (Fig. 7). Through measurements and comparisons, it was found that the forming effect was adequate and the forming error was small, conforming to the expected forming result. It has been demonstrated that the theory of spiral free-bending forming, proposed in this paper, has strong practicability and reliability.

The diameter D of a spiral column is an important parameter of spiral tubes. For precision and small parts, the spiral diameter D of the mounted spiral tube is required to be small. The simulation results indicated that the values of eccentricity U and distance A are the main factors affecting the spiral diameter, as shown in Fig. 8. The spiral diameter D decreases with the increasing eccentricity U. Moreover, the decrease in spiral diameter D is faster when the eccentricity is small, while it slows down when the eccentricity is larger. That is, the eccentricity U is inversely proportional to the spiral diameter D. On the contrary, the spiral diameter D increases with the increase of distance A. That is, the eccentricity U is directly proportional to the distance A. In the simulation and the forming process, it was found that the eccentricity U
cannot increase indefinitely. There is a maximum eccentricity \( U_{\text{max}} \), and its size is closely related to the structure of the die (Fig. 9).

![Figure 8. Influence of eccentricity U and A on spiral diameter](image)

**Figure 8.** Influence of eccentricity U and A on spiral diameter

As it can be seen in Fig. 9, there are two positions where a limit of motion exists. One of them is the motion limit of the spherical bearing and the bending die, and the other is the motion limit of the bending die and the guider. These two limits constrain the upward movement of the spherical bearing, thus the eccentricity cannot further increase. When the distance A is fixed, there is a maximum eccentricity \( U_{\text{max}} \), which defines the minimum bending radius \( R_{\text{min}} \). Different free-bending devices have different \( U_{\text{max}} \).

According to the forming procedure of the existing free-bending equipment, the minimum spiral diameter \( D \) is:

\[
D \geq 6d \quad (1)
\]

where \( d \) is the tube diameter.

![Figure 9. The motion limit diagram of free bending device](image)
In addition, the spiral diameter is affected by the mechanical properties of the material. Materials with good bending properties provide spiral tubes with smaller spiral diameters. On the other hand, materials with poor bending performance, generally increase the eccentric distance $U$ and decrease the distance $A$, leading to a series of quality defects in the formed workpieces. As it can be seen in Fig. 10, the forming process can cause wrinkling at the inside of the bend, cause large cross-section distortion, and even break the tube.

4. Conclusion
In this study, the process analysis of spiral tubes based on the 3D free-bending technology was presented. Moreover, the relationship between the free-bending parameters and the spiral bending parameters was investigated. According to the simulation results, the main factors that influence the spiral diameter include eccentricity $U$ and distance $A$. More specifically, the diameter of the spiral decreases continuously with the increase of the eccentricity, showing an inverse correlation. On the contrary, the diameter of the spiral increases with the increase of the distance $A$, showing a direct correlation. Based on the existing 3D free-bending equipment, the minimum spiral diameter $D$ was 6d.

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