Wrinkling instability and mandrel design of thin walled tube

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Abstract—In view of the wrinkling and instability phenomenon in the bending process of thin-walled pipe, the factors such as bending die, pipe material, bending technical parameters and bending equipment are analyzed. The ideal pipe fitting method is achieved by designing the chain disk mandrel, reasonably selecting the number of mandrel chain plates and mastering its correct use method.

1. INTRODUCTION
The thin-walled tube mainly refers to the parts formed with tube as blank, and its forming is an important part of advanced plastic processing technology.

(a)Wrinkle phenomenon
From the point of view of mechanical analysis, wrinkling is the external macroscopic manifestation of plate or shell buckling and large post buckling deformation under certain local compressive stress[1-2]. In essence, wrinkling can be regarded as the secondary equilibrium path deviating from the basic equilibrium path (the path starting from zero load). That is, because the size of thin-walled parts in one direction is far smaller than that in other directions, when the internal compressive stress of the plate and shell surface reaches the critical compressive stress, due to the small disturbance, the local in-plane deformation is easily transferred to the out of plane bending along the thickness direction, which is called compression instability deformation [3-4].

2. REVIEW ON WRINKLING OF THIN WALLED PARTS
   - Wrinkling research based on experiment
     In the early stage of wrinkling research, the methods of wrinkling research and prediction are mainly based on experimental experience[5]. The experiment plays an important role in exploring the cause, formation and elimination of wrinkling[6-8]. In essence, it is a method to gradually make the working pressure stress approach the unknown process parameters when the critical compressive stress is approached[9]. It is necessary to combine with other research methods such as theoretical analysis and reasonable design of test scheme to obtain the conditions of wrinkling[10]. YBT [11]test, as a method which can provide reference for the wrinkle resistance of different plates and determine the deformation trend of sheet metal, is highly valued. Reddy studied the plastic wrinkling of pipes by experimental method. He applied bending moment to both ends of stainless steel pipe and aluminum pipe, and
measured the maximum principal strain of wrinkling instability. Compared with the theoretical analysis results of circular tube under uniaxial compression and pure bending, it was found that tube flattening had little effect on tube instability and wrinkling, and the main reason for wrinkling was the drum generated during the bending process. The results obtained by the quantity (J2 deformation) theory are more consistent with the experimental results than the incremental (J2 flow) theory. However, Reddy[12] only got some empirical cognition on the wrinkling of pipes through experiments, but did not make in-depth discussion on its internal mechanism.

- **Wrinkling research based on theoretical analysis**

  Theoretical analysis method is another important method to analyze the instability and wrinkling in metal forming process. The analysis idea is: establish the analysis model, and then use differential equilibrium equation to solve directly or approximate analysis by energy method. However, due to the complexity of wrinkling instability and the limitation of theoretical analysis methods, most of the theoretical studies are focused on some relatively simple problems, such as the ring subjected to internal tension, the column subjected to axial loading, the annular plate bent with a central conical die, etc. Although there are some basic criteria, the conclusions are not enough to be fully applied to engineering practice, especially for the forming process with complex boundary conditions, such as tube bending.

- **Two theoretical methods to study wrinkling**

  **Bifurcation theory:** the single value theory of plastic bifurcation (sufficient condition for the uniqueness of elastic-plastic materials) is one of the analytical methods widely used to judge wrinkling. This theory was put forward by Hill[13] in 1958. It began to apply the dynamic criterion to the plastic Wrinkling Analysis of materials, thus providing an important idea for the study of wrinkling. After that, Huchison[14-16] further refined Hill’s bifurcation theory and applied it to the wrinkling analysis and prediction of thin plates and shells. The basic idea is: when the Hill bifurcation functional or its derivative form, such as Hutchinson functional, has non-zero solution, wrinkling occurs. In this theory, it is considered that the point where wrinkling begins is the point where the basic equilibrium path bifurcates.

  **Energy method:** the energy method was proposed by senior in 1956, which provides another important method for the study of critical conditions of wrinkling such as drawing process and tube bending process. The basic steps of wrinkling prediction based on energy method are as follows:

  1. The critical wrinkling energy $W$ was calculated by energy method;
  2. The plastic deformation energy $T$ is calculated by analytical equation or numerical method;
  3. Comparing $W$ with $T$, wrinkling will occur when $T$ is greater than $W$.

  Senior[17] used the energy method to solve the wrinkling problem studied by geckerer, and deduced a more accurate formula for the critical pressure of wrinkling.

**3. USING FINITE ELEMENT METHOD TO DEAL WITH WRINKLING OF THIN-WALLED TUBE**

Because most of the thin-walled parts forming process is a complex physical process under the interaction of multiple factors, involving geometric nonlinearity, material nonlinearity and boundary nonlinearity. The combination of finite element simulation technology and corresponding plastic wrinkling criterion is a main method to analyze material wrinkling after analytical analysis and experimental research, which is widely used in the instability prediction and analysis of various complex forming processes. This method has incomparable advantages in research and design cost compared with traditional experimental research methods and analytical analysis methods.

At present, there are two methods based on the finite element method to model the buckling phenomenon: implicit method and explicit method. In essence, the implicit method is a linear eigen analysis. For linear problems which are independent of stiffness matrix, loading and displacement, eigen analysis is an appropriate method, but it is difficult to predict wrinkling in forming without initial defects. However, the explicit method is nonlinear incremental analysis. In applications with material or geometric nonlinearity, nonlinear incremental analysis method is needed, which can automatically generate the deformation mesh when wrinkling occurs. However, the explicit method is sensitive to the type of elements, mesh density and convergence rate. Most of the softwares have the ability of
wrinkling eigenanalysis. Although the numerical simulation method based on finite element method provides a powerful means for the study of buckling and wrinkling of thin-walled parts, how to make the analysis results reliable, effective and convenient for application is still a challenging work.

4. MAIN FACTORS AFFECTING BUCKLING AND WRINKLING OF THIN-WALLED TUBES
The bending process of thin-walled tube is an extremely complex nonlinear physical process, and the influence of forming parameters on buckling and wrinkling is a complex multi factor coupling problem. In the case of pure bending, when the pipe with outer diameter D and wall thickness s is bent under the action of external force moment M, the pipe wall outside the neutral layer is thinned by the tensile stress, and the inner pipe wall is thickened by the compressive stress. The inner tube wall may wrinkle and lose stability under the action of R2. The main influencing factors are as follows:

1. Geometric parameters: bending radius, relative pipe diameter, mandrel extension;
2. Material parameters: hardening index;
3. Boundary condition parameters: friction between tube blank and anti wrinkle block, friction between tube and mandrel, clearance between tube blank and anti wrinkle block.

The hardening coefficient of the material, the rotational speed of the bending die, the pushing speed of the briquette, the friction factor between the tube blank and the bending die, and the friction factor between the tube blank and the pressing block have little influence on the buckling and wrinkling.

5. DESIGN AND SELECTION OF MANDREL
In order to bend the ideal pipe fittings, corresponding measures should be taken to prevent the above defects, and the mandrel bending is one of the most commonly used effective methods. The mandrel and the flexible core head can rotate with the bending of the pipe, and the connection belongs to the combination of translational connection and rotary connection.

The so-called mandrel bending refers to the method in which a suitable mandrel is inserted into the tube during the bending process when the relative bending radius R / D or relative wall thickness s / D of the bent pipe is small. A ball chain plate and a spring instead of the head plug are connected in series to form the mandrel to prevent flattening and wrinkling at the circular arc when the pipe is bent(See Fig.3)

This paper takes the two inch thin-walled tube used in a large road maintenance machinery as an example. The specification of the thin-walled pipe is 55.80mm (outer diameter) x 1.65mm (wall thickness), bending radius r = 90mm, bending angle 90 ° to design a set of die and its use method.

The relationship between the values of R / D, S / D and α, the bending mode and the number of ball chain plates is shown in Table 1. The satisfactory effect can be achieved by referring to this table when bending.
Table 1 Selection of the number of chain plates for mandrel bending

| S/D ≥ | 1/3 | 0.25 | 0.20 | 1/6 | 1/7 |
|-------|-----|------|------|-----|-----|
| R/D   | 90° | 2    | 3    | 3   | 4   | 4   |
|       | 180°| 3    | 3    | 4   | 5   | 5   |
| 1.5   | 90° | 2    | 3    | 3   | 4   | 4   |
|       | 180°| 3    | 3    | 4   | 5   | 5   |
| 2     | 90° | 2    | 3    | 2   | 3   | 3   |
|       | 180°| 2    | 3    | 3   | 4   | 4   |
| 2.5   | 90° | -    | 2    | 2   | 3   | 3   |
|       | 180°| 2    | 2    | 3   | 4   | 4   |
| 3     | 90° | -    | -    | 2   | 2   | 3   |
|       | 180°| -    | -    | 2   | 3   | 4   |

According to the diameter, wall thickness, wall thickness and bending angle of thin-walled pipe, S / D = 0.03, R / D = 1.5, bending angle of 90° and combined with the recommended number of ball chain disks in the table above, the mandrel with four chain discs is selected for thin-walled tube bending operation.

6. CONCLUSION
(1) In order to prevent the tube from wrinkling in the process of bending, it is convenient to use the bending die to prevent the tube from wrinkling;
(2) The mechanism of buckling and wrinkling is still a common and difficult problem in thin-walled parts forming, especially for the three-dimensional forming process with complex boundary conditions, such as hydroforming and tube bending;
(3) Because the combination of energy method and finite element method can capture the wrinkling bifurcations in the forming process of thin-walled parts, both the computational efficiency and the calculation accuracy can be taken into account;
(4) With the development of computer, finite element algorithm and mechanics, dynamic criteria such as bifurcation theory can be easily applied to the prediction and research of buckling and wrinkling in the future.

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