Method of simulation modeling and computing analysis for tube bending

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ABSTRACT: Simulation of thin-walled tube bending process not only results in a large amount of calculation due to its high nonlinearity, but also leads to its non-uniqueness in simulation modeling because of the particularity and diversity of the mandrel structure. The paper proposes a method for the simulation analysis of molding process of tube bends, which combines coordinate translation with mass scaling and is called the equivalent method, and gives out super-elastic mandrel model describing working state of mandrel more reasonable. It deduces the basic formula of the equivalent method which takes transformation of time coordinate, meanwhile keeps spatial coordinates not transform, and controls the calculation amount by controlling the time of banding molding and time step of recursive solving. It validates correctness and validity of the equivalent method and the mandrel model, which shows that the super-elastic mandrel models could avoid blindness, and the equivalent method greatly raises the simulation efficiency, and has enough analysis precision.

1. Introduction

As the same with the problems of kinetics simulation analysis for sheet metal forming, collision impact etc, due to highly nonlinear of the problem the magnitude of time steps for simulation analysis of tube bending process is always microsecond, so the calculation steps required is above $10^6$ because the time domain for simulation is usually in seconds, the computation time for simulation is very large. For the stamping process, actual process time is about one second. While bending process time generally is about 4~8 seconds (for continuous tube bends, the longer), its computation time is much longer. How to improve the computational efficiency under the premise of ensuring the simulation accuracy becomes a concerned matter for engineering application.

Mandrel is the most complex part of the tube bending mold, it plays a supporting role for tube wall, thus improves the molding defects [1]. Due to the particularity and diversity of the mandrel structure and the mandrel structural difference for different specifications it results in its non-uniqueness of simulation modeling at the tube bending process. Li Heng et al [2] studies the mechanism of friction in simulation of plastic forming with thin-walled tube NC rotary draw bending, which models contact state between the mandrel shank and balls using connection element with motion attributes called hinge. Zhang Jingjing et al [3] uses nodal ball hinge to describe contact state between shank and balls in the study of effects of assistant pushing on wall thinning and spring back in NC bending process of thin-walled aluminium alloy tube with large diameter. Du Hongwei [4] uses bar element to simulate ball on LS-DYNA, through compiling source to achieve hinge, but bar element with only three degrees of displacement freedom, the ideal describing ball hinge is difficult.

The relationship of mesh density, computational efficiency and calculation accuracy based on ANSYS/LS-DYNA are discussed in the reference [5]. In the reference [6] the computational
efficiency and accuracy of collision simulation are discussed from five aspects which contain mesh density, number of integrating point in the shell element thickness direction, element formula, contact type, hourglass control. In order to improve the computational efficiency, Bao Yidong [7] puts forward an improved compressed storage scheme, called the one dimension array with variational bandwidth for the iterative method, to solve the efficiency problem when solving finite element equation in the self-development numerical simulation software for sheet metal forming. For computational efficiency problem of a multi-contact dynamic system a contact constraint hidden or activation method is proposed to reduce the dimension of Jacobean matrix when iterating to improve the efficiency [8].

To reduce simulation time and improve computational efficiency, special methods are used to accelerate the simulation process, such as the speed acceleration for the sheet metal forming simulation, through raising the punch motion velocity factitiously, namely in sheet forming boundary condition enlarging loading velocity could reduce computational time, which is called virtual forming velocity. The reference [9] analyzes influence of punch speed for the simulation results in typical stamping process, and gives out that when ratio of system kinetic energy and internal energy is less than 5% increasing punch velocity could improve computational efficiency and ensure enough analysis precision. Wang peng et al [10] simulates drawing process for cross beam of automobile chassis and discusses the influence of virtual punch velocity on simulation results. Hu Weicai et al [11] studies the influence of improving the speed of the virtual stamping on sheet metal bending simulation, by comparing the test it shows that when the virtual punching speed does not exceed a threshold limits speed, the accuracy is guaranteed.

The punching speed is important process parameters for stamping process, the reference [12, 13] study the influence of punch velocity to hot stamping forming for 5182 aluminum alloy and ultrahigh plate, and gives out that as the punch velocity increases, the sheet strain rate increases, limiting drawing ratio (LDR) decreases, and risk of tension crack increases. The punch velocity given by the reference is in the range of 0.1~1.5 mm/s and 35~350 mm/s, but virtual forming velocity generally is 2000~3000 mm/s.

Another example is the mass scaling method, i.e., the quality of some particular element is enlarged to increase the time step, but scaling factor is trial, and has large randomness, so it can not be popularization and application.

For this highly nonlinear problem of the tube bending process, in order to shorten the simulation time and improve the computational efficiency under the premise of ensuring the simulation accuracy it is one of technical difficulties in the simulation analysis.

2. Bending Simulation Foundation

Fig1 is schematic diagram of tube bends processing, it includes bend die, clamp die, wiper die, pressure die and mandrel, where the bend die and clamp die with a tube rotate around the center of the bend die at a certain rotational speed in order to achieve the bend molding. Bending speed and friction conditions between dies and tube are the main bend processes. Mandrel is the most flexible part in dies, according to molding requirement it may include a number of balls, and the style of connection for balls is flexible.

The quality index of tube bend processing is considering the bends sectional thickness changes, i.e. rate of thinning and thickening, and the changes in the degree of bends-sectional distortion, called ellipticity. The thickness ratio of maximum value among the thinning in bending cross-section after bending and the thickness before bending is defined as rate of thinning, the thickness ratio of maximum value among the thickening in bending cross-section after bending and the thickness before bending is defined as rate of thickening, the ratio of the maximum diameter minus minimum diameter caused by the change of cross-sectional shape and the diameter before bending is defined as ellipticity. The details for the quality index are different depending on the specific requirements of different diameter and thickness of the tube bending.

It is easy to appear the problems such as spring back, wrinkling, cross section distortion, thinning, and tension crack during tube bend processing. In order to reduce these defects appeared in tube bend
processing, computer simulation is the best way. The simulation foundation of bend molding is structure dynamics with geometric and material nonlinearity considering contact. Where, large deformation reflects in geometric equation, elastic-plastic deformation reflects in physical equation, interaction between tube moulds reflects in contact boundary conditions, the balance equation (that is motion equation) shows in formula (1).

\[ \sigma_{i,j} - \rho u_{i,t,t} - \mu u_{i,t} + f_i = 0 \]

Where, \( \sigma_{i,j} \) is stress tensor, \( \rho u_{i,t} \) is inertia force, \( \rho \) is density, \( u_{i,t} \) is second derivative for displacement vector, that is acceleration, \( \mu u_{i} \) is viscous force, \( \mu \) is damping coefficient, \( u_{i} \) is first derivative for displacement vector, that is velocity.

Fig.1 Schematic diagram of tube bends processing

Because of nonlinearity of equation (1) it is difficult to get analytic solution, only solution by numerical method. In order to guarantee stability of the algorithm, solving time step should be less than the threshold time step, the threshold time step is shown by the following formula:

\[ \Delta t_{\text{min}} = l_{\text{min}} / \sqrt{E/(1-\nu^2)\rho} \]

Where, \( l_{\text{min}} \) is element smallest size, \( \rho \) is material density, \( E \) is material elastic modulus, \( \nu \) is Poisson ratio. The formula (3) is often used to get time step when simulating the forming, the bending process by use of LS-DYNA and ABAQUS in engineering.

In order to improve the computational efficiency, rigid simplified model\(^{[14]} \) is used generally, i.e., bend die, clamping die, wiper die, pressure die and insert die are taken as rigid body, only considering interactional surface part between dies and tube, as shown in fig2. But modeling for mandrel has no uniform way.

Fig.2 FEM rigid simplified model

Despite the rigid simplified model reduces the computation time for simulation, but the computation time is still great, especially when the number of balls increases because of the highly nonlinear problems.
3. Equivalent Method and Mandrel model

Approach of the equivalent method for tube bend processing is that it takes time transformation, meanwhile keeps spatial coordinates not transforming, and it finishes simulation calculation on the standard time domain[0,1], or in smaller time domain according to the situation. Transformation of time is as follows:

\[ t_i = \alpha t \]  

(3)

Where, \( \alpha \) is transform factor, this leads to the actual bending time domain \([0, T]\) transform to the equivalent simulation time domain \([0, T_1] = [0, \alpha T]\). Obviously, if it takes \( \alpha = 1/T \), then \( T_1 = 1 \), that leads to the actual bending time T transform to the equivalent simulation time 1. Other values also may be less than 1, which can transformation into smaller time domain. The equivalent simulation time domain \([0, 1]\) is called standard time domain.

Then structural dynamic equation (1) is transformed to:

\[ \sigma_{i,j} - \alpha^2 \rho u_{i,\alpha t_i} - \alpha^2 q u_{i,\alpha t_j} + f_i = 0 \]

\( t_i \in [0, T_1], \ i = x, y, z \in \Omega \).

(4)

Initial conditions from boundary conditions are transformed to:

\[ t_i = 0, \ u = u_0, \ \nu_{i0} = v_\nu / \alpha \]

(5)

Tube bending process sometimes also contains the rotation angular velocity \( \omega \) of the bending die, and could be calculated from the formula \( \omega = v / R \) (R is bending die radius) by the bending speed, the initial angular velocity transformation is calculated as:

\[ \omega_i = \omega_\nu T = v_\nu T / R \]

(6)

Thus the tube bending problem (1) is transformed into equivalent problem (4) by the transformation of time domain (3). Obviously, the size of tube dies of problem (1) is consistent with (4) in topological relations, and therefore the finite element mesh model have no changes. Since the transformation changes the initial conditions of material parameters and boundary conditions, the material density of problem (4) changes into \( \rho = \rho \alpha^2 \), the bending velocity changes to (5, 6).

Because the equivalent simulation time domain is in \([0, 1]\) or more smaller domain, if the time step of recurrence solving is unchanged, the number of calculation steps will be considerably reduced, so it’s effectively shorten the calculation time in the bending process simulation analysis. And the simulation results with the actual tube bending process in time domain \([0, T]\) is consistent.

Calculation in the molding process simulation is decided by the time steps required in the solving domain. From the time domain transformation and the formula (4) and (5) it could see that the speed is increased, the time domain is reduced and the material density becomes smaller. And the threshold time step for solving reduces the same multiple for the same problem and same grid, the derivation is shown in equation (7).

\[ \Delta t_i = l_{\min} / \sqrt{E / (1 - \nu^2) \rho_i} = l_{\min} / \sqrt{E / (1 - \nu^2) \rho_0} = \alpha \Delta t_{\min} \]

So the transformation results is that time domain scales \( \alpha \) times (shown in equation (3)), but the time step also scales \( \alpha \) times (shown in equation (7)), whereby the number of steps required to calculate is unchanged.

In order to improve computational efficiency, the computational time step required for solving shouldn’t change in pre-and post time coordinate transformation. After that the time domain becomes smaller, but the step is not changed, and the total number of steps is reduced.

The formula (7) also shows that after transforming the time coordinate, mass density of smallest element (the element corresponding to \( l_{\min} \)) in finite element mesh model will be scaled to enlarge the time step, and then to ensure the calculation time step is constant.

Thus, the algorithm scales mass density of smallest element after the time coordinate transforming, in order to increase element density, so enlarge time step. But the key is that how to select the mass density scaled factor, and it is difficult to receive satisfactory results for the cut and try way. The
algorithm receives best mass density scaled factor deduced by (7), which requires threshold time step unchanged in pre-and post time coordinate transformation. It is increasing mass density of smallest element, that is:

\[ \rho_i = \rho_i / \alpha^2 \]  

Where, \( i \) is element number of required mass density scaled, the smallest element; \( \rho_i \) is the mass density after transforming the time coordinate.

In the above formula, \( i \) also could be part number of mass density required scaling. This is favorable to practical engineering applications. In the use of simulation software analysis, meshing is done automatically, and for a large number of meshes, looking for the smallest element is very difficult by hand. But it could be set the parts needing mass density scaling artificially, and its mesh density is controlled, which is met the requirement of the smallest element.

Finally, the steps for transforming time domain into the equivalent simulation time domain are summarized as follows:

1) Transform factor: \( \alpha = 1/T \)  
2) Time domain: \([0, 1]\)  
3) Tube density: \( \rho_i = \rho_i / \alpha^2 \)  
4) Initial velocity: \( v_{i0} = v_i / \alpha \)  
5) Density scaled: \( \rho_i = \rho_i / \alpha^2 \) (one part)

This method which combines coordinate translation with mass scaling is called the equivalent method, which could effectively reduce the number of calculation steps. Because rigid simplified model for bend molding die set all die parts as rigid, so it could not be scaled by mass density, and only tube could be scaled by mass density when using this method for bending analysis.

This paper proposes super-elastic model for mandrel of rigid simplified model shown in Fig3. Now there are rigid ball hinge and rigid pin hinge simulation model for mandrel \(^{2,3,15}\), it simplifies shank with ball hinge and pin hinge respectively. As shown in Fig2 mandrel contains shank and balls. Ball plays a supporting for tube wall so as not to collapse and do not wrinkle and the role of shank is to connect each ball to make them to successfully be token out after bending \(^{16}\).

With the view of the motion constraint, the role of shank is to apply constraints for balls that limit the random motion of the ball and make it move only in the required direction \(^{17}\). For rigid simplified model, the simulation do not concern force and deformation of the shank, only require that the balls can be provided reasonable constraints, to ensure that the balls do required rotation.

The super-elastic model sets the balls as rigid, but the shank is set as super-elastic body, their interaction are reflected by friction; Super-elastic body provides a degree of freedom for ball rigid body motion, it can make the ball get reasonable freedom through adjusting the super-elastic material parameters. The rigid hinge model is suitable for the mandrel with joint type; studying hinge model could get reasonable spacing between the balls. The advantages of the super-elastic body used flexible shank are: objectively reflect material properties of the shank and apply constraints on balls reasonably.

![Frictional contact](Image)

Fig.3 super-elastic mandrel model
4. Examples and Analysis

Here one example is given to illustrate the effectiveness of the algorithm. For the same tube bending problem, the bending quality index is used to compare the results using different mandrel models and different algorithms. All calculations are finished on ANSYS/LS-DYNA.

This thin-walled tube’s material is 304 stainless steel, an outer radius is 25mm and the wall thickness is 0.6mm. The bending angle is 90°, bending radius is 150mm. Bend process: bending speed is 0.4 rad/s, bending time \( T = 3.93s \). This is a typical thin-walled stainless steel tube bending with large aspect ratio for diameter and thickness, so it is great difficult to bend.

Because the tube wall-thickness is too thin, bending wrinkle and collapse defects are prone to emerge, so mandrel tool is used, as shown in figure 4, here 7 balls ensure the smooth shape. Using super-elastic mandrel model increases the number of contact pairs between tube and the balls, which increases the bending simulation time significantly. The calculation time is 17739 seconds, about 5 hours for conventional means.

![Fig.4 Settings of 304 stainless steel thin-walled tube](image)

This computational model has two parts which could be density scaled after transforming, one is tube, and another is mandrel. So here it gives two schemes to compare the effect of the two parts. Scheme 1: takes mandrel for mass density scale based on formula (10~14), 

\[
\frac{smvm}{4.2371} = \omega, \quad \frac{srad}{1.5721} \quad \rho = 0.5115 \times 10^{-6} \text{kg/mm}^3.
\]

The equivalent bending time is 1s. Simulation time is 8099s (About 2 hours 15 minutes).

Scheme 2: takes tube for mass density scale, the calculation is 5048s (About 1 hour 24 minutes). The comparison between conventional simulation calculation and above two schemes for thinning rate of wall thickness is shown in figure 5. For scheme 1, the thinning rate gap was 1.4%, the gap thickening rate was 1.4%; for scheme 2, the thinning rate gap was 0.9%, the gap thickening rate of 1.3%. The sectional ellipticity is calculated using the following formula through post-processing analysis of simulation software to find changes in cross-sectional shape of the cross-section.

\[
\phi = \frac{(d_{\text{max}} - d_{\text{min}})}{d}
\]  

Where: \( d_{\text{max}} \)—the maximum outer diameter dimension of same section after bending; \( d_{\text{min}} \)—the minimum outer diameter dimension of same section after bending; \( d \)—the outer diameter dimension of same section before bending.

The largest cross-section change is shown in figure 6 according to the results of different schemes calculated by using conventional simulation and two schemes, where the elliptical cross-section are 3.11%, 1.7% and 4.6% respectively. The results not only meet the quality requirements of bending, but also are relatively close.
5. Experimental Verification

To verify the accuracy of the proposed mandrel model, consider a thin-walled tube, material is Q235, tube radius is 18.7mm, wall thickness is 1mm, the bending angle is 90 degree, bending radius is 100mm. Bending process: bending speed is 0.8 rad/s, bending time $T = 1.96s$. Simulation are carried out using three mandrel models. In order to compare with the analysis simulation results conveniently, curved section of the tube is marked with reticule before bending, then the labeled tube is mounted into the groove of the bending die appropriately, and the clamping die is clamped, at last the mandrel is pushed into the hollow tube for 90 degree bend test.

From the figure 6 it could be seen that after bending 90° the wall thinning rate of tube is up to 10.01%, the wall thickening rate is up to 8.152% using rigid ball hinge model. The wall thinning rate of tube is up to 9.331% using rigid pin hinge model, the wall thickening rate is up to 8.449%. The wall thinning rate of tube is up to 9.737% using super-elastic connection model, the wall thickening rate is up to 8.064%. For the results using three mandrel models the section of tube for every 15° at 0°~90° is taken to get the thinning rate, thickening rate and ellipticity of the sections, and then change curves could be obtained. The simulation results compared with experiments are shown in figure 7.
As seen above, the trends of three models’ simulation results are almost the same, and error between simulation and experimental values are also within the allowable range. Rigid ball hinge model and rigid pin hinge model limits the balls’ horizontal movement ideally, it only could rotate; and super-elastic connection model allows a certain degree of linear displacement on condition that the ball rotation is ensured. Obviously, the rigid hinged model can only offers constraints for the balls to ensure the normal bend-shaping, but it can not reflect the material properties of the mandrel, therefore the rigid hinge model is mainly used for process analysis of the tube bending process. The super-elastic connection model could obtain the deformation and stress state of the mandrel in simulation analysis of the tube bending process, not only the process can be analyzed for the tube bending process, but also the material properties and dimensions of the mandrel could be studied.

6. Conclusion
Due to a large amount of highly nonlinear simulation calculation, it puts forward the equivalent method which combines coordinate translation with mass scaling. It overcomes the blindness of changing a physical variable unilaterally when attempting to accelerate the simulation efficiency. And it gives out super-elastic mandrel model to solve the problem of mandrel modeling uncertainty in tube bending simulation. Not only it greatly improves the computational efficiency of the molding process simulation analysis, but also ensures the accuracy of analysis. This facilitates practical and engineering application of the tube bending process simulation and analysis.
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