Investigating the Time-course of Spline Cold Roll Forming Process: A Numerical Simulation Study

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Abstract. The cold forming process of spline is a kind of high speed plastic forming technology. It is generally difficult to observe the whole process through experiment, and the simulated analysis is still insufficient for cold roll forming intensive research. This paper simplified the model of spline cold roll forming, simulated the cold forming process of spline based on Deform 3D software. With the right teeth shape derived from the biting, rough roll forming, fine roll forming and seceding, teeth shape change, cutting tool interface change and the forming stress are analyzed in detail. The forming force is obtained by simulation and its change rule is analyzed. Time-course of spline cold roll forming process simulation and results obtained in this paper can provide references for further research on optimization of cold forming technology and forming machine design.

Introduction

Owing to the virtues of self-centering, large carrying capacity, long life, high precision and high degree of interchangeability [1], involute spline is widely used in automobile, machines tools, engineering machinery and other industries [2]. Cold roll forming technology is a new manufacturing method with high efficiency, high accuracy and high material utilization. Compared with its widely practical application in production line, literature survey shows it is still few theoretical rearches that have been carried out in this field. Liu[3-4] conducted the finite element simulation of the involute spline and obtained the quantitative result of the elastic response of the cold rolling spline. Wang[5] simulated the cold roll forming process of precise spline shaft with Deform-3D, and analyzed the forming force and deformation characteristics of workpiece and forming mold. An[6] expatiated the processing technology of the spline cold extrusion. High-speed cold roll forming is generally difficult to observe and study the whole process and relative parameters in the time-course of the forming through experimental method, and in-depth analysis of the numerical simulation in this field is still insufficient from the present literature. This paper is based on the numerical simulation of the various phases and forming forces of the spline cold roll forming process, to provide references for further research on optimization of cold forming technology and forming machine design.

Model and Algorithm of Cold Rolling Process Simulation

A rigid plastic model is utilized for metal plastic forming. The boundary equation and boundary condition of the rigid plastic problem are defined by basic equations as following[7]:

(1) Balance equation

\[ \sigma_{ij} = 0 \]  

Where \( \sigma_{ij} \) is the stress tensor.

(2) The relation between velocity and strain rate: the geometric equation
\( \dot{\varepsilon}_o = (v_{,i} + v_{,j}) / 2 \)  

(2)

Where \( v_i \) is velocity and \( \dot{\varepsilon}_o \) is strain rate.

(3) Constitutive relationship

\[ \dot{\varepsilon}_o = \dot{\lambda} \sigma'_o \]  

(3)

Here \( \sigma'_o \) is instantaneous stress; \( \dot{\lambda} = \frac{3}{2} \) is constitutive relations in which \( \ddot{\varepsilon} = \frac{2}{\sqrt{3}} (\dot{\varepsilon}_i \dot{\varepsilon}_i) \) is equivalent strain rate and \( \sigma = \sqrt{\frac{3}{2} (\sigma_x \sigma_x)} \) stands for equivalent stress.

(4) Mises yield criteria

\[ \sigma = Y \]  

(4)

Where \( Y \) is material yield stress. \( Y = \sigma_i \) for ideal rigid-plastic material; \( Y = f (\sigma) \) for rigid-plastic hardening material; \( Y = f (\sigma, \dot{\varepsilon}, T) \) for rigid viscoplastic material.

(5) Volume incompressible condition

\[ \dot{\varepsilon}_v = \nabla \cdot \varepsilon_o = 0 \]  

(5)

Where \( \dot{\varepsilon}_v \) is volume deformation rate and \( \delta_{ij} \) is Kronecker delta.

(6) Boundary conditions (Control equations)

Control equations contain stress boundary conditions and velocity boundary condition:

\[ \sigma_o n_j = \bar{P}_i \]  

(6)

\[ v_i = \bar{v}_i \]  

(7)

Where \( n_j \) is the component of the unit normal vector at any point on the surface \( S_p \); \( \bar{P}_i \) stands for equivalent surface force and \( \bar{v}_i \) is equivalent velocity.

Translating the above partial differential equation into a variational functional extremum problem is the basic algorithm for the following simulation of the cold rolling spline process.

**Cold Roll Forming Process**

The working principle of spline shaft cold roll forming is shown in figure 1. In the process of teeth, the two rub teeth board (rack die) move in synchronised with each other. Rub teeth board is fixed in each slider, and the workpiece is placed on the top between the two boards. The contact between rub teeth and shaft blank drives the shaft blank to rotate around the top, and the workpiece is pressed after rolling. The outer surface extrudes a series of grooves and projections. After the workpiece is rotated several revolutions, the required spline is formed to complete the cold forming process.

![Figure 1. Schematic of cold roll forming.](image)

The rub teeth board has hundreds of teeth with different geometry parameters. The whole process of spline teeth forming is divided into four phases including biting, rough roll forming, fine roll
forming and seceding. The two parts of the rub teeth boards are exactly the same when the number of splines is even, and the two pieces are staggered by half of the pitch when the number of splines is odd.

Modeling and Simulation Results

The relevant parameters of spline and the corresponding rack die used in the simulating example are shown in table 1 and figure 2 respectively.

| Parameters                  | Symbols | Values       |
|-----------------------------|--------|--------------|
| Modulus                     | m      | 1            |
| Number of teeth             | z      | 35           |
| Pressure angle              | \( \alpha \) | 30°         |
| Blank diameter              | \( d_{f} \) | \( \phi 34.94 \pm 0.01 \) |
| Major diameter of spline    | \( d_{a} \) | 36.1\( \pm 0.16 \) |
| Minor diameter of spline    | \( d_{f} \) | 33.95\( \pm 0.25 \) |
| Dental plate width          | b      | 40           |
| Accuracy level              | grade  | 6            |

Figure 2. Structure diagram of rack die.

The Establishment of Cold Forming Simulation Model

According to the condition of plane deformation \( B/H > 4.5 \) for the cold forming simulation model (where \( B \) is the tooth width, \( H \) is the full height of tooth [8]) and the tooth height of spline \( H \) is 1.075mm, the width of the blank \( B \) is defined as 5mm. In actual application, shaft length with spline is generally longer than 20mm and obviously satisfies the plane deformation condition which means the volume ratio between the convex and the concave close to 1 during the plastic deformation. A “shorter” shaft model in analysis can effectively reduce the amount of calculation. Another factor needed to consider is to restrict the bulges on the both end face of blank. To this end, an axial constrain mold is added to the blank. Simulation model of blank and the constrain die are shown in figure 3.
Figure 3. Simplified axial constrain mold and blank.

Figure 4 shows the initial position of simulation model and both rack die of cold roll forming process. With this, the reasonable simplification of the model is established to ensure the following simulation process can run efficiently with acceptable accuracy.

Figure 4. The initial state of cold roll forming.

Preprocessing of Cold Roll Forming Simulation

By importing the previous stl format model, setting the blank material to 45 steel and rigid body for the dies and boards, a new task is created in Deform-3D software. The outer cylindrical ring of the blank is mesh-subdivided since the main deformation occurred in this region during the forming process. The total number of division meshes is up to 123604, as shown in figure 5. The length of the smallest grid unit is set to 0.28mm which is determined by testing to ensure the convergence of the solution process and ensure the authenticity and accuracy of the simulation.

Figure 5. Meshes of the blank.

The friction and lubrication between blank and rack die are affected by the thickness of the oil film, the surface quality of the blank and rack die, the pressure and the sliding speed [9]. In the process of cold rolling, all these factors are constantly changing. It is inaccurate to use the Coulomb friction and shear friction model to describe it. However, to obtain accurate friction performance, a large number of friction performance tests are required. Here according to the existing research results, set the friction type to Coulomb friction, and set the friction coefficient to 0.3.

The feed step length is set to approximate 1/3 of the minimum unit side length, which is 0.1 mm. According to the actual processing conditions, set the feed speed of the rake plate to 200mm/s.
Preview the simulation motion process and confirm that the database file has been generated and complete the preprocessing of simulation.

**Cold Roll Forming Simulation Results**

The results of the spline shape obtained by the software simulator are shown in figure 6. There is no fold phenomenon in the steps of the entire simulation process. That is, the situation that the mesh does not have a large-scale continuous folding or entrance to the interior of the metal. It also shows the feasibility of parameter setting in previous preprocessing.

![Figure 6. Overall and partial enlarged outline of spline.](image)

**Metal Flow Rate Analysis**

For predicting the shape and size of the deformed body, designing the processing parameters and mold and conducting the quality analysis [10], The flow rate of metal during cold rool forming is analyzed, as shown in figure 7.

![Figure 7. Velocity of metal flow.](image)

Figure 7(a) indicates the metal flow velocity increasing gradually from the center of the spline model to the outer concentric circular, and the minimum flow velocity near the center of the circle is 0.707 mm/s. The metal flow rate reaches maximum value 250 mm/s where the blank is in contact with the rack die. From figure (b), it can be seen that the four velocity contour lines F, G, H, and I are deformed at the biting position due to the continuous extrusion between the tool and the workpiece.
Figure (c) shows that the metal flow direction inside the spline is the tangential direction of the circle in the process of cold roll forming, and rapid increasing in value and chaos in direction of the speed nearby the contact point are shown in figure (d).

**Cold Roll Forming Process Analysis**

Based on the simulation results of the above forming process, the following four phases of involute spline cold rolling are specifically analyzed.

**Biting Phase**

The main task in this phase is to divide the teeth accurately where a series of shallow concave-convex surface on the blank shaft are revealed, as shown in figure 8(a) and (b). The condition of correct division is 
\[
Z_{\text{min}} = \frac{\pi}{\arctan \mu} + 1,
\]
where \(Z_{\text{min}}\) is involute spline minimum number of teeth and \(\mu\) is the friction coefficient between workpiece and mold [11]. With appropriate bite angle and distance of rack die, feed of forming in biting phase gradually increases to ensure correct spline teeth profile to come into being in next phase.

![Overall view](image1)

![Partially enlarged view](image2)

![Equivalent stress overall view](image3)

![Equivalent stress magnification view](image4)

Figure 8. Phase of biting.

Figures (c) and (d) show the overall and partial view of the equivalent stress at this phase. It can be seen that the equivalent stress is up to 992Mpa in the area around contact point and concentrated in the groove. Figure (c) also shows the streses in the blank is not completely symmetrical, and it is an inherent feature of the half-pitch dislocations of two rack die boards for the odd number of spline teeth (so it can be seen there are stress distribution around the central hole). The results of non-uniformity of the stress caused by odd number of spline teeth and other additional dynamic load (such as vibration or errors) on the center hole can provide reference for the design of the top device, where the force is normally being considered negligible.
Rough Roll Forming Phase

Figure 9 shows the rough roll forming phase of the spline, which further increases the degree of the groove and the projection on the basis of the deviding teeth. Materials of blank is further extruded into teeth on rack die and the complete tooth shape gradually forms.

![Overall view](image1)

![Partially enlarged view](image2)

![Equivalent stress overall view](image3)

![Equivalent stress magnification view](image4)

Figure 9. Phase of rough roll forming.

Figures 9 (c) and (d) are views of the equivalent stress at this phase. It can be seen that the areas with larger stress and strain are still mainly appeared in the cold roll region of the blank. Compared with the process of dividing teeth phase, the top part of the spline tooth is subjected to a greater stress due to the top surface of the shaft is in full contact with the bottom of the teeth on rack die. On the other hand, the stress at the center hole is much smaller than in the biting phase because with the constant shaping of the tooth in blank, the motion between the rack die and the spline shaft gradually approaches the gear motion of rack and pinion.

Fine Roll Forming Phase

Figure 10 shows the phase of the further shaping of the teeth profile and spline finish. At this phase, two surfaces of rack die are parallel to each other, and the mutual movement between the mold and shaft can be regarded as the gear motion of rack and pinion. However, the rack die still has a modification on the splines, and the tiny deformation generated in blank is mainly concentrated on the surface of the spline teeth which has a finishing effect.

![Overall view](image5)

![Partially enlarged view](image6)
Figures (c) and (d) show the overall and partial view of the equivalent stress at this phase. It can be seen that the stress is almost completely concentrated in the tooth, that is, only the teeth is modified.

**Seceding Phase**

Figure 11 shows the seceding phase of spline cold roll forming. Due to the tooth profile angle on rack die (which is opposite direction of biting phase), the spline shaft does not press against the rack die at this phase. Spline disengaged from rack die with slight elastic recovery.

Figures (c) and (d) are the overall and partial views of the equivalent stress at this phase. Stress at this phase is small but still exists. Shaft rotates along with rack die and seceding without pressure on the spine teeth.

**Forming Force Analysis and Discussion**

The force of the cold roll forming can be divided by the radial and tangential direction of the spline shaft called the radial forming force \( F_r \) and the tangential forming force \( F_t \), as shown in figure 12. Axial forces along shaft axis are negligible.
Figure 12. Schematic diagram of forming force.

Figure 13 shows the simulation results of real-time changes in radial and tangential forces testing from one of the die plate.

There are several sudden changes in the forming force in figure 13 because of reorganization in the grid, as shown in figure 14. The corresponding strain rate is extremely large, reaching 54400mm/mm•s, and resulting in a large sudden change in the extrusion force, which is an error in the simulation and can be removed during the force analysis.
It can be seen that the radial force and tangential force of the die boards are relatively large during the biting, rough roll forming phases, and there is still a certain amount of tangential force in the seceding phase. As discussed previously, in seceding phase spline shaft is still driven to rotate by die plates, and only no compression in the radial direction.

Conclusion

The time-course of spline cold roll forming process is investigated by numerical simulation in this paper. The correct teeth shape is obtained and the characteristics of metal flow in spline shaft is reviewed. Four phases which is biting, roughing, fining, and seceding in the spline cold rolling process are analyzed in detailed, and the stress and teeth shape change in each phase are listed and discussed. Through the simulation, the forming force and variation law of the spline cold rolling process are also obtained. The above studies can provide the reference and data supports for the optimization of the spline cold rolling process and the design of the cold forming equipment.

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