Simulation Analysis of Cylinder Winding Prestress Based on Ansys

Jiaqing Li¹, Dayu Zheng¹*, ChaoDong¹, Zhen Zhang², Feng Wang², Yongmei Wang¹ and Xigui Wang⁴

¹School of Light Industry, Harbin University of Commerce, No.1, Xuehai Street, Songbei District, 150028, Harbin, China.
²Tianjin Diguang Electromechanical Equipment Co., Ltd., No.19 Shuangchen East Road, Economic Development Zone, Beichen District, 300400, Tianjin, China.
³School of Automobile and Traffic Engineering, Heilongjiang Institute of Engineering, No.999 Hongqi Street, Daowai District, 150050, Harbin, China.
⁴School of Engineering Technology, Northeast Forestry University, No.26, Hexing Road, Xiangfang District, 150040, Harbin, China.
*E-mail: zhengdayu2000@126.com

Abstract. Based on the distribution and layer characteristics of the prestressed steel wire-wound cylinder of the four-column hydraulic press, its supporting parts not only bear the constant stress caused by internal pressure, but also withstand the alternating stress caused by the steel wire-wound cylinder, and then produce gradual accumulation of plastic deformation. This paper uses theoretical calculation formulas to solve the corresponding parameters, establishes a three-dimensional constitutive model, uses Ansys workbench to optimize its thermo-solid coupling simulation, and compares with the theoretical calculation results to verify the rationality of the design of the prestressed winding cylinder with cooling loading. The design of prestressed steel wire winding cylinder of 400MN plate hydraulic press is combined. Setting cylinder rated working pressure of 88MPa, an inner diameter of 1500mm, its wire winding layers are divided into 10, 8, 6, 4 and 2. Based on the comprehensive analysis of the simulation results, the optimum initial stress table number of steel wire winding is obtained. According to the optimum initial stress table number, the influence law of preload coefficient on the design parameters of prestressed steel wire winding cylinder block is analyzed.

1. Introduction
In the 17th century, people reinforced the barrels of guns by winding, which played a role in pre-tightening protection. Due to the advantages of light weight, high strength and long fatigue life, prestressed winding technology has been favored by technical personnel in various fields, especially in the application of high pressure vessels, prestressed concrete structures and prestressed winding frames. Yan Yongnian carried out a lot of research on steel wire winding cylinder and frame, laid a theoretical foundation, and successfully designed and manufactured 360 MN vertical steel pipe extruder. Relevant studies have shown that the pre-stressed steel wire winding ultra-high pressure cylinder has a high fatigue life. The winding steel wire used does not produce creep works below 900 MPa and 80 °C, and the pressure loss is also small. Compared with the traditional high pressure cylinder, it has the advantages of high pressure, high fatigue life, small size, light weight and low cost [1-2].

At present, domestic and foreign manufacturers use prestressed steel wire winding cylinder. The
structure has the advantages of large bearing capacity, high fatigue strength, safe, reliable and no explosion risk [3]. At present, the research of prestressed steel wire winding hydraulic cylinder at home and abroad is mainly carried out by APDL parametric design of Ansys finite element analysis software, and the prestressed steel wire winding cylinder is simplified as a plane stress problem for finite element simulation. Simplifying the plane stress problem can save a certain amount of calculation time, but the simplified model will have a certain error in settlement. In recent years, due to the continuous powerful computer calculation function and the continuous improvement of Ansys finite element analysis software Workbench, this paper designs and simulates the three-dimensional model of 88 MPa ultrahigh pressure prestressed steel wire winding cylinder according to theoretical analysis and Ansys Workbench.

2. Calculation of Cylinder Parameters

Many scholars in China and abroad have carried out extensive research on the results of wire winding. According to different requirements and conditions, they are mainly divided into the following three kinds of winding methods: equal tension, equal shear stress, and equal shear stress. Through experiments and a large number of practical engineering applications, it is found that the failure of steel wire is not caused by the normal stress failure, but caused by the shear failure. So this paper applies an equal shear winding method to calculate.

A 400 MN plate hydraulic press in a factory in Tianjin is designed as cylinder rated working pressure of 88MPa. The inner diameter of the cylinder is 1700 mm, the material of the cylinder is 40CrMn, the elastic modulus \( E = 206 \, \text{GPa} \), the Poisson’s ratio \( \mu = 0.3 \), the yield strength under modulation and the safety factor \( n_s = 1.6 \), so \( \frac{\sigma_s}{n_s} = 343.75 \, \text{MPa} \). Using equal shear winding method, the winding material is 65Mn, the allowable stress is 900MPa, the preload coefficient \( \eta = \frac{\sigma_s}{\left( \frac{\sigma_s}{n_s} - \mu P_b \right)} = 1.1288 \), that is \( \eta = 1.2 \).

2.1. Determination of Outer Diameter of Winding Cylinder

Outer diameter of winding cylinder

\[ r_0 = 1.36 \sqrt{\frac{n_s P_b}{E \eta \sigma_s}} \]  
(1)

obtained by calculation \( r_0 = 1138.05 \, \text{mm} \),
In order to meet the safety requirements and obtain the maximum profit, fetch \( r_0 = 1139 \, \text{mm} \).

2.2. Core Outer Diameter

Equal shear stress winding is to make the shear stress of each layer of steel wire in the composite state equal, in the composite state, any layer has

\[ \tau = \frac{\sigma_{tr} - \sigma_{rr}}{2} = \frac{[\sigma]}{2} \]  
(2)

Considering the balance of the steel wire layer from any radius \( r \) to the outer radius \( r_0 \) of the winding cylinder, there are

\[ \sigma_{tr} = \frac{1}{r} \int_{r}^{r_0} \sigma_{tr} \, dr \]  
(3)

Substitution (2)

\[ \sigma_{tr} + \frac{1}{r} \int_{r}^{r_0} \sigma_{tr} \, dr = [\sigma] \]  
(4)

The upper integral

\[ r \frac{d\sigma_{tr}}{dr} = [\sigma] \]  
(5)
Resolve available

\[ \sigma_T=\sigma^* \left[ 1+\ln \frac{r}{r_0} \right] \]  

(6)

Substitution (2)

\[ \sigma_r=\sigma^* \ln \frac{r}{r_0} \]  

(7)

\[ \sigma_j=\sigma^* \ln \frac{r}{r_0} \]  

(8)

In the synthetic state, the inner pressure \( p_b \) and the outer pressure \( \sigma_j \) keep balance, and the tangential synthetic stress of the inner wall at this time is

\[ \sigma_{th}=p_b \frac{k_j^{*+1}}{k_j^{*-1}}+\sigma_j \frac{2k_j^{*2}}{k_j^{*-1}} \]  

(9)

But \( \sigma_{th}=\sigma_{gtb}+\sigma_{ptb} \). Bring in the upper available

\[ p_b \frac{k_j^{*+1}}{k_j^{*-1}}+\sigma_j \frac{2k_j^{*2}}{k_j^{*-1}}=\frac{1}{\eta} \sigma \]  

(10)

Bring (8) into (10) and simplify

\[ p_b \frac{k_j^{*+1}}{k_j^{*-1}}+\sigma_j \frac{2k_j^{*2}}{k_j^{*-1}}=\frac{1}{\eta} \sigma \]  

(11)

For the convenience of calculation

\[ A=\left( \frac{p_b^{*+1} \sigma}{2[\sigma]} \right)^{1/\eta}, \quad B=\left( \frac{p_b^{*} \sigma}{2[\sigma]} \right)^{1/\eta} \]  

(12)

Equation (11) can be further simplified as

\[ A+\frac{B}{\eta}=\frac{\ln r_j}{r_j} \]  

(13)

According to equation (13), the outer diameter of core tube \( r_j=1037\text{mm} \) can be obtained by trial algorithm.

2.3. Determination of Initial Stress

Prestressed steel wire winding hydraulic cylinder using flat steel wire, from the above calculation shows that the 88Mpa pre-stressed ultrahigh pressure winding layer winding layer number of 68 layers. In order to ensure the accuracy of the Ansys simulation results and reduce the amount of calculation, we divide the steel wire layer into two layers of initial stress step, according to the initial stress formula.

\[ \sigma_0=\sigma^* \left( 1+\ln \frac{r_0}{r_i} \right) p_b \frac{2r_i^2}{r_i^2-r_0^2} \]  

(14)

The calculation results are shown in table 1

**Table 1.** The initial stress load applied in the winding process of two-layer initial stress step.

| Tier number | R1-r2(mm) | Initial stress(MPa) |
|-------------|-----------|---------------------|
| 1           | 1037-1088 | 751.1               |
| 2           | 1088-1039 | 676.9               |

2.4. Radial Displacement of Inner Wall of Mandrel

By formula
\[
\Delta_{gb} = r_b \varepsilon_{gb} = r_b \frac{\sigma_{gb}}{E} = \frac{r_b \sigma_0}{E} \ln \frac{r_0^2 - r_b^2}{r_j^2 - r_b^2}
\]  

(15)

Determine the radial displacement of the inner wall of the cylinder after each initial stress step winding, as shown in table 2.

**Table 2.** Radial displacement of inner wall of mandrel in winding process.

| Tier number | 1  | 2  |
|-------------|----|----|
| \( r_1 - r_2 \)(mm) | 1037-1088 | 1088-1139 |
| \( \Delta_{gb} \)(mm)  | 0.83 | 0.53 |

As can be seen from the above table, the winding process is divided into 2 layers of initial stress steps, the core wall radius shrinkage 0.83 + 0.53 = 1.36 mm.

After winding, the shrinkage of inner wall radius of mandrel is

\[
\sigma_{gb} = -\sigma_0 \ln \frac{r_0^2 - r_b^2}{r_j^2 - r_b^2}
\]  

(16)

\[
\Delta_{gb} = r_b \varepsilon_{gb} = r_b \frac{\sigma_{gb}}{E} = \frac{850 - 327.75}{206000} = 1.35
\]  

(17)

Similar to the calculated shrinkage (1.36 mm).

Cylinder after winding, will lose stability, meet the equation

\[
\frac{1}{(K_j^2 - 1) (1 + \mu^2) (K_j + 1)} K_j^2 \ll \left[ \sigma \right]
\]  

(18)

Resolved 10431.97 Mpa > 343.75 Mpa, So it won’t lose stability.

3. The Establishment of Finite Element Model of Prestressed Steel Wire Winding Cylinder

3.1. Establishment of 3d Model

The simplification of the geometric model is the most critical step in the establishment of the finite element model. In order to simplify the analysis model, some small thickness differences caused by connecting thread holes and tolerance zones are omitted. The initial stress stage of the steel wire is simplified as a whole cylinder. The cylinder assembly is composed of two layers of steel wire, cylinder core and upper and lower steel wire baffles. The solid element SOLID186 is used to simulate the actual model. As shown in figure 1, the analysis efficiency is improved without affecting the analysis results. The simplified model is saved as a ‘stp’ format. In figure 1, 1 is the core crown and 2 is the steel wire baffle,3 is a steel wire layer.

![Figure 1. Three - dimensional structure of cylinder.](image)

3.2. Ansys Finite Element Analysis

Finite element method (FEA) [4-5] is an important numerical simulation technology, which is an important part of computer aided engineering technology. It can handle complex boundary conditions
and models of different materials under the condition of ensuring accuracy, so as to predict the internal stress and strain of the results. It is the most widely used numerical calculation method in the engineering field, and is widely used in structural analysis and mechanism optimization in the engineering field. For the prestressed cylinder, the shrinkage of the inner wall of the core cylinder end by winding steel wire is crucial for the design of the pre-tightening cylinder. The finite element analysis is used to verify whether the shrinkage of the inner wall of the cylinder is consistent with the calculation results, and whether the design of the prestressed steel wire winding cylinder is reasonable. The initial stress steps of steel wire winding are 10 layers, 8 layers, 6 layers, 4 layers and 2 layers for simulation analysis, and the simulation results are comprehensively analyzed to obtain the optimal number of initial stress stages of steel wire winding.

The model of '.stp' format was imported into Ansys workbench 2020R2, and the thermo-solid coupling analysis of the cylinder was carried out: the density of the material was defined as 7.85 g/cm³, the Young's modulus was 206 GPa, the Poisson's ratio was 0.3, and the yield strength was 343.75 MPa. In order to make the simulation results accurate, the pre-stressed steel wire winding cylinder is meshed by eight-node hexahedral element using Multizone, and the mesh size is set to 20 mm. In order to make the mesh element quality better, the inner wall of Core Chrysanthemum is meshed by surface mesh. The finite element model after mesh generation is shown in Figure 2. After meshing, 829564 nodes and 172174 elements are generated.

![Figure 2. Finite element model.](image)

### 3.3. Contact Settings

In this paper, the thermal-solid coupling method is used to simulate and analyze the winding process of 88 MPa ultra-high pressure hydraulic cylinder. The mutual contact between the steel wire layers, between the steel wire layer and the cylinder, and between the cylinder and the steel wire baffle can be regarded as a contact problem to solve. The core crown and the steel wire baffle are set as bonded, the steel wire baffle is the target surface, and the TARGE174 unit is used to define. The core crown is the contact surface, and the COMTA170 unit is used to define. The core crown and steel wire are set as Frictional, steel wire is the target surface, defined by TARGE174 unit, core crown is the contact surface, defined by COMTA170 unit. Frictional is set between the steel wire and the steel wire baffle. The target surface of the steel wire baffle is defined by TARGE174 element, and the steel wire is the contact surface, which is defined by COMTA170 element. Frictional is set between the steel wire layers, and the inner ring is the contact surface, which is defined by COMTA170 element. The outer ring is defined as the target surface using the TARGE174 unit. Friction coefficient set at 0.3.

### 3.4. Application of Initial Winding Stress

Considering that the direct application of initial stress on the steel wire is complex, the cooling and compression method is adopted, that is, the temperature of the steel wire layer is reduced to make the steel wire shrink, and the shrinkage stress of the steel wire leads to asymmetric cyclic compressive stress. The relationship between temperature and load is shown in equation (19). The initial stress is transformed into temperature as shown in table 3, where α is the thermal expansion coefficient of steel, taking $12 \times 10^{-6}$.

$$\sigma_0 = -E^*\alpha^*\Delta T$$  \hspace{1cm} (19)
Table 3. Equivalent temperature load applied during winding.

| Tier number | 1       | 2       |
|-------------|---------|---------|
| Initial stress (MPa) | 751.1   | -303.9  |
| Temperature (°C)     | 676.9   | -273.8  |

3.5. Analysis of Simulation Results

![Displacement Cloud](image1)
![Shear Stress Nephogram](image2)

Figure 3. Finite element analysis cloud map of core chrysanthemum after two-layer initial stress step winding.

Figure 3 is the cloud chart of the displacement and shear stress of the core tube at the end of the two-layer initial stress step winding. As shown in the analysis results of figure 3, the maximum radial displacement inside the core tube is 1.300 mm after the steel wire winding of the second layer of initial stress step is completed, and the shrinkage of the inner wall radius after the winding is basically consistent with the theoretical calculation value, and the error value is 3.7%. The maximum radial shear stress of the core tube is 140.96 MPa, which is less than the shear yield limit of the material of 230 MPa, which meets the design requirements.

3.6. The Influence of Steel Wire Layers with Different Initial Stress Steps on Prestressed Wound Steel Wire Cylinder

There is a certain error between the finite element results and the calculation results of the above analysis when the steel wire is divided into two layers of initial stress step winding. Considering the influence of the number of different initial stress stage layers of steel wire on the winding results, the wire winding results of different initial stress stage layers are analyzed, and the number of initial stress stage layers closest to the theoretical calculation results is found. The number of initial stress stage layers of steel wire is divided into four, six, eight and ten layers. According to equation (14) and (19), the initial stress of each layer of initial stress step winding and the temperature of each layer of initial stress step under cooling and pressure are obtained. The finite element analysis setting is consistent with the above analysis.

Based on the finite element analysis of five kinds of pre-stressed winding cylinders with different initial stress stages, the data is obtained, as shown in table 4, and the line figure 4 is drawn to make the analysis more intuitive.

Table 4. The analysis results of stratum number of five initial stress stages.

| Tier number | \( \Delta_{gb}(mm) \) | Error | \( \Delta_{gb}(MPa) \) |
|-------------|-----------------|-------|-----------------|
| 2           | 1.30            | 3.7%  | 140.96          |
| 4           | 1.30            | 3.7%  | 144.89          |
| 6           | 1.314           | 2.6%  | 146.06          |
| 8           | 1.315           | 2.58% | 146.18          |
| 10          | 1.318           | 2.37% | 146.53          |
According to the table 4 and figure 4, the shrinkage of the inner wall of the core tube wrapped by the ten-layer initial stress step is 1.318 mm, which is more close to the calculated value of 1.35 mm than that of the inner wall of the core tube wrapped by the eight-layer initial stress step, the inner wall of the core tube wrapped by the six-layer initial stress step, the inner wall of the core tube wrapped by the four-layer initial stress step and the inner wall of the core tube wrapped by the two-layer initial stress step. The shear stress of the inner wall of the ten-layer initial stress step winding is 146.53 MPa, which is 146.18 MPa, 146.06 MPa, 144.89 MPa and 140.96 MPa higher than that of the inner wall of the eight-layer initial stress step winding, the inner wall of the six-layer initial stress step winding, the inner wall of the four-layer initial stress step winding and the inner wall of the two-layer initial stress step winding. Therefore, the more the number of the initial stress stage of the steel wire, the more similar the finite element analysis results and the calculation results, and the pretightening effect is better.

According to the analysis in figure 4, when the simplified layer number of the initial stress step of the steel wire is 6 or more, the shear stress and shrinkage of the inner wall of the core chrysanthemum tend to be stable. It can be inferred that the pre-tightening force of the cylinder is almost unchanged when the initial stress step of the pre-tightening steel wire is 6 or more. In the actual winding process, if there are too many initial stress stages, the change of the pre-tightening force is relatively frequent, there will be large errors. Therefore, the comprehensive analysis shows that the number of layers of the initial stress stage of the steel wire of the pre-stressed steel wire winding cylinder is the most appropriate.

4. Influence and Selection of Preload Coefficient

The prestressed structure must be pre-tightening to a suitable degree. If the pre-tightening is too tight, it will destroy or make the structure size too large in the pre-tightening process. If the pre-tightening is too loose, the pre-tightening component will not be properly protected, and the working load will be damaged. Therefore, the pre-tightening coefficient $\eta$ is used to quantitatively describe the pre-tightening “loose” or “tight”. In order to ensure high fatigue strength, the pre-tightening coefficient $\eta>\eta_0=[\sigma_s]/([\sigma_s]-\mu P_b)=1.1288$.

From the above analysis, it can be concluded that the initial stress stage of steel wire winding is divided into six layers as the calculation basis. From the equation (1), it can be seen that the selection of pre-tightening coefficient directly affects the size of the outer diameter of the winding steel wire, and then affects the wall thickness of the core crown, the size of the prestress and the number of steel wire layers. Table 5 is the change of each parameter when the pre-tightening coefficient is different. It can be seen that the greater the pre-tightening coefficient, the wall thickness of the core cylinder, the number of steel wire layers, and the greater the stress. The winding parameters under several different pre-tightening coefficients are calculated according to the theory, which meet the requirements. However, from the perspective of cost, the smaller the pre-tightening coefficient, the smaller the thickness of the core crown and the number of steel wire layers. The lower the cost is, the smaller the preload coefficient is, and the better it is under the condition of ensuring high fatigue strength.
Table 5. Comparison of winding parameters of 400 MN cylinder under various preload coefficients.

| Preload coefficient | $R_0$(mm) | $R_f$(mm) | Steel wire layers | $\sigma_0$(MPa) |
|---------------------|-----------|-----------|-------------------|-----------------|
| 1.2                 | 1139      | 1037      | 68                | 826.7           |
| 1.3                 | 1185      | 1077      | 72                | 847.6           |
| 1.4                 | 1230      | 1100      | 80                | 863.3           |
| 1.5                 | 1273      | 1150      | 82                | 868.0           |
| 1.6                 | 1315      | 1189      | 84                | 873.3           |
| 1.7                 | 1355.5    | 1210      | 97                | 892.6           |
| 1.8                 | 1394.5    | 1240      | 103               | 898.2           |

5. Object of 400MN Plate Hydraulic Cylinder

Figure 5a is the physical object of the winding cylinder of the 400 MN sheet hydraulic press designed according to the parameters analyzed in this paper. Figure 5b is the physical picture of the 400 MN sheet hydraulic press. After one year of use, the user feedbacks that the hydraulic press and the hydraulic cylinder are in good condition and the user is satisfied.

![400 MN wire winding hydraulic cylinder](image1)
![400 MN plate hydraulic press](image2)

**Figure 5.** The physical drawing of 400 MN half-chip hydraulic press.

6. Conclusions

In this paper, the finite element analysis software Ansys is used to simulate the results of steel wire winding of 88 MPa prestressed winding ultra-high pressure hydraulic cylinder. In the analysis process, the friction contact between the steel wires and between the steel wire and the cylinder is considered to simulate the real winding condition as much as possible. The pressure is cooled and pressurized. The shrinkage of inner diameter and the shear stress of core chrysanthemum in the winding process are analyzed by thermal-solid coupling method and the calculation results are compared to verify the rationality of the design of prestressed winding cylinder. The following conclusions are drawn:

(1) Through the finite element analysis of the steel wire winding with the steel wire layers divided into layers, 4 layers, 6 layers, 8 layers and 10 layers of initial stress steps, it is concluded that the more the number of the initial stress stage layers is, the better the pre-tightening effect is. However, when the number of the initial stress stage layers of the steel wire is more than 6 layers, the shear stress and shrinkage of the inner wall of the core chrysanthemum tend to be stable. Considering the actual winding process, the number of the initial stress stage layers of the steel wire is set to be 6 layers.

(2) The traversal calculation method was used to study the winding parameters of the 400 MN equal shear stress steel wire winding hydraulic cylinder model under different pre-tightening coefficients. Through comparative analysis, the greater the pre-tightening coefficient is, the greater the wall thickness of the mandrel, the number of steel wire layers, and the initial stress are. Through the
analysis of comprehensive conditions such as cost, under the condition of meeting the minimum pre-tightening coefficient, the smaller the pre-tightening coefficient is, the lower the cost is.

(3) Through theoretical analysis and finite element calculation, the key technical parameters of wire winding of 400 MN hydraulic cylinder under 88 MPa internal high pressure were determined, and according to these technical parameters, the oil cylinder of 50 MN plate hydraulic machine was designed.

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