Gas Packaging Container Based on ANSYS Finite Element Analysis and Structural Optimization Design

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Abstract Gas packaging containers are often used for flammable, explosive, toxic, strong corrosion and compressed gas packaging. The transportation and use environment is more complicated and harsh than other metal packaging containers, and has very high requirements for its structural design. In this paper, taking a certain type of industrial oxygen cylinder as an example, ANSYS Workbench is used to establish the finite element model, and the equivalent linearization treatment method is used to optimize the structural design of the gas cylinder, which provides ideas and methods for the optimization design of the gas packaging container structure.

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1. Introduction
Gas packaging containers are an integral part of the packaging industry. They are often used for flammable, explosive, toxic, strong corrosion and compressed gas packaging. The transportation and use environment is more complicated and harsh than other metal packaging containers, so the structure design is very High requirements are attributed to special equipment in China, and relevant laws and regulations are formulated for special management.

As an important industrial material, industrial gas is widely used in the fields of machinery, chemical industry, metallurgy, aerospace, medical and health, and daily life of residents. As a gas container for industrial gas packaging, it is widely used in social production and life. Taking a certain type of industrial oxygen cylinder as an example, this paper uses ANSYS Workbench to carry out finite element analysis of the oxygen cylinder during transportation to obtain the stress value and distribution of the oxygen cylinder during transportation, and apply the equivalent linearity to the existing safety hazards. The structural optimization method is used to optimize the structure design, which provides an idea and method for the optimization design of gas packaging container structure.

2. Structural Analysis of Gas Packaging Containers

2.1 Main Characteristics of Gas Packaging Containers
In addition to the very high quality requirements for the inner surface of the gas packaging container, it should also comply with the national pressure vessel quality standards. The gas cylinder is a kind of gas packaging container. According to the "Cylinder Safety Supervision Regulations", it usually refers to the re-inflatable use under normal environment (-40~60 °C). The nominal working pressure is 1.0~30MPa (gauge pressure). A mobile pressure vessel with a nominal volume of 0.4 to 1 000 L and containing permanent gas, liquefied gas or dissolved gas.
2.2 Oxygen Cylinder Structure

The oxygen cylinder is a steel cylindrical high-pressure vessel for storing and transporting industrial oxygen. It is generally made of seamless steel pipe and is a kind of permanent gas cylinder. It is an indispensable material equipment in industrial production. The common oxygen cylinder wall thickness is 5-8mm, and its shape, structure and standard should meet the requirements of GB5099 "Steel Seamless Gas Cylinder" [1]. The research object of this paper is limited to industrial 40L oxygen cylinder, the nominal pressure is 15MPa, and its appearance structure parameters are shown in Table 1:

| Outer Diameter | Bottle Wall Thickness | Nominal Pressure | Actual Pressure | Material | Length |
|----------------|-----------------------|------------------|-----------------|----------|--------|
| 219mm          | 5.7mm                 | 15MPa            | 12.5MPa         | 32Mn2V   | 1450mm |

Because the oxygen cylinder is subjected to a dangerous accident due to external force, the action point of the external force is usually concentrated on the bottom of the bottle, the shoulder of the bottle and the bottle body, so the bottle mouth and the bottle valve area are simplified. In addition, the bottom position of the bottle is convenient for calculation and is limited to a concave structure. The concave part structure should meet the design requirements of GB5099 [1]:

(1) \( S_1 = (2.0 \sim 2.6) \) \( S \)
(2) \( S_2 = (1.8 \sim 2.2) \) \( S \)
(3) \( S_3 = (2.0 \sim 2.6) \) \( S \)
(4) \( r = (0.07 \sim 0.09) \) \( D_0 \)
(5) \( H = (0.13 \sim 0.16) \) \( D_0 \)

Where \( S \) is the thickness of the oxygen bottle wall and \( D_0 \) is the outer diameter of the oxygen bottle, as shown in Figure 1 [1]:

![Figure 1 Design Requirements for The Concave Bottom of the Oxygen Cylinder](image)

According to the design requirements, the selected values are shown in Table 2:
Table 2 Selected Model Values

|        | S (mm) | \(1/2D_0\) (mm) | S_1 (mm) | S_2 (mm) | S_3 (mm) | r (mm)  | H (mm) | L (mm) |
|--------|--------|-----------------|----------|----------|----------|---------|--------|--------|
|        | 5.7    | 109.5           | 14.25    | 11.4     | 14.25    | 17.52   | 32.85  | 1450   |

2.3 Oxygen Cylinder Force Analysis
The oxygen cylinder material is 34Mn2V structural steel, which is a plastic material. We can use the fourth strength theory to judge the static structure analysis result of the gas cylinder. The stress is calculated by the following formula:

\[
\sigma_{eq} = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}
\]

Among them, \(\sigma_1\), \(\sigma_2\), and \(\sigma_3\) are represent the first principal stress, the second principal stress and the third principal stress, respectively.

The main loads that gas cylinders are subjected to during transportation are: gas pressure inside the bottle, external air pressure, acceleration load caused by transportation, and gravity load on the cylinder itself. The normal working pressure of the gas cylinder is 12.5 MPa, assuming it is evenly distributed on the inner surface of the cylinder. The bottle body is affected by the external atmospheric pressure, and the atmospheric pressure is assumed to be 1.01 MPa, which is evenly distributed on the outer surface of the oxygen cylinder. The bottle body is also affected by its own gravity, and the gravitational acceleration is assumed to be 9.8m/s^2, and the direction is vertically downward. In addition, because the oxygen cylinder is under transport conditions, it is bound to be affected by the acceleration of the car during road travel. Considering the complex and variability of the driving situation of the road during road transportation, it is limited to the special case of the emergency braking of the truck, and its acceleration is 5m/s^2.

3. Finite Element Analysis and Structural Optimization Design of Oxygen Cylinder
3.1 Finite Element Analysis of Oxygen Cylinder
The 40L industrial oxygen cylinder is generally made of 34Mn2V. Due to the trace element alloy vanadium, it has been widely used in the manufacture of high pressure seamless gas cylinders [2]. Its main mechanical properties are as follows [3]:

(1) Density: 7850 Kg/m3
(2) Poisson's ratio: 0.3
(3) Modulus of elasticity (Young's modulus): 185000 MPa

Automatic meshing in the Mechanical module, assuming that the cylinder is upright during transportation, and is constrained by two restraining bands at the cylinder body, and the constraint is firm and reliable, so the cylinder model is set to adopt cylindrical surface restraint gas, the axial and radial directions of the bottle are fixed. After the loading is completed, the finite element model can be solved. The finite element analysis results are shown in Figure 2:
Figure 2 Stress on The Oxygen Cylinder

The maximum stress is 259 MPa and the minimum is 4 MPa. According to the data, the tensile strength of 34Mn2V structural steel $\sigma_b$ is about 745 MPa, and the yield strength $\sigma_y$ is about 530 MPa. According to the "GB150-2011 Pressure Vessel"\(^{(4)}\), the allowable stress should take the smaller value between $\frac{\sigma_b}{3.0}$ and $\frac{\sigma_y}{1.5}$.

\[
\frac{\sigma_b}{2.7} = 276 \text{ MPa} \tag{2}
\]

\[
\frac{\sigma_y}{1.5} = 353 \text{ MPa} \tag{3}
\]

\[
[\sigma] = \frac{\sigma_b}{3.0} = 248 \text{ MPa} \tag{4}
\]

It can be seen that under the assumption that the stress intensity of the cylinder is very close to the allowable stress, there is a safety hazard, so it is necessary to optimize the structure.

3.2 Oxygen Cylinder Structural Optimization Design

The total stress experienced by the pressure vessel during actual use is the superposition of multiple stresses such as film stress, bending stress, and thermal stress. Different stresses have different discriminant criteria, and a single stress exceeding the allowable value may cause danger. When designing and analyzing the stress condition and structural safety of the pressure vessel, if only the calculated nominal film stress or bending stress is compared with the allowable stress alone to optimize the wall thickness, there is a possibility that exists hidden safety dangers. Therefore, it is necessary to perform equivalent linearization on the pressure vessel.

The linearization process is to calculate the stress distribution curve and linearize it according to the principle of static equivalence, and decompose it into: film stress equivalent to the resultant force and evenly distributed along the thickness of the section; equivalent to the combined force. The bending stress and the peak stress of the section thickness are linearly distributed for checking separately.

The film stress calculation method is as follows:

\[
\left(\sigma_{ij}\right)_m = \frac{1}{e} \int_{-\frac{e}{2}}^{\frac{e}{2}} \sigma_{ij} dz \tag{5}
\]

The bending stress calculation method is as follows:

\[
\left(\sigma_{ij}\right)_b = \frac{12z}{e^3} \int_{-\frac{e}{2}}^{\frac{e}{2}} \sigma_{ij} z dz \tag{6}
\]

In the formula, $\sigma_{ij}$ represents each stress component, $\left(\sigma_{ij}\right)_m$ represents film stress of each...
stress component, \( (\sigma_{ij})_b \) represents the bending stress of each stress component, \( e \) indicates the thickness of the cross section, \( z \) represents the coordinate system along the path \(^5\).

For the stress equivalent linearization of the cylinder, the point of analysis should be specified first, and then the path of the analysis should be determined to perform the calculation. This paper selects the maximum stress point for analysis.

When using finite element analysis software for analysis, the path should be determined first, and then the stress distribution curve is obtained by fitting the stress at each point on the path to calculate the value of each stress \(^6\). The selection of the calculation path generally follows the following principles:

1. Generally selected in the discontinuous part of the geometry, including the maximum point of stress, or may also be selected at the shortest path of the two dangerous surfaces;
2. In the plate-and-shell type, the mid-surface normal passing through the maximum point of stress is generally selected. For the wall thickness change, a straight line passing through the minimum wall thickness direction of the maximum stress point is generally selected;
3. Set the path along the direction in which the crack is most likely to expand \(^5\).

The maximum stress calculated in this paper is located at the arc transition between the bottle body and the bottle shoulder, which is the discontinuous part of the geometry mentioned above, so the calculated calculation path is the shortest path along the wall thickness of the maximum stress point. The equivalent linearization treatment results of the oxygen cylinder are shown in Figure 3:

![Figure 3 Results of Equivalent Linearization of Oxygen Cylinders](image)

Membrane is classified into a total film stress \( P_m \), Bending is summarized as a bending stress \( P_b \), and Peak is a peak stress \( F \). Referring to the standards of other scholars, from a more secure point of view, the total stress value is summarized as (primary film stress) + (primary bending stress), that is, \( P_L + P_b \) \(^7\). With reference to national standards, the safety factors and assessment results of the above several stresses are shown in Table 3:

| Tabular Data | Membrane [Pa] | Bending [Pa] | Membrane+Bending [Pa] | Peak [Pa] | Total [Pa] |
|-------------|---------------|--------------|-----------------------|-----------|-----------|
| Length [n]  | 1.366e+008    | 1.267e+008   | 2.567e+008            | 1.402e+005| 2.589e+008|
| 1           | 1.216e+004    | 1.366e+008   | 2.516e+008            | 1.858e+005| 2.517e+008|
| 2           | 2.432e+004    | 1.366e+008   | 2.404e+008            | 2.318e+005| 2.465e+008|
| 3           | 3.648e+004    | 1.109e+008   | 2.413e+008            | 2.78e+005 | 2.414e+008|
| 4           | 4.852e+004    | 1.056e+008   | 2.367e+008            | 3.243e+005| 2.362e+008|
| 5           | 6.015e+004    | 1.037e+008   | 2.311e+008            | 3.705e+005| 2.311e+008|

| Type of Stress | Analog Value/MPa | Safety Value/MPa | Evaluation Results |
|----------------|------------------|------------------|--------------------|
| \( P_m \)      | 137              | [\( \sigma \)] = 279 | Safe              |
| \( P_L + P_b \) | 127              | [1.5\( \sigma \)] = 419 | Safe              |

Table 3 Stress Assessment Results

Under the set conditions, the maximum stress of the oxygen cylinder is at the arc transition between the bottle body and the shoulder of the bottle. Although the stresses are individually checked and meet the safety requirements, the oxygen bottle is close to the allowable value. The maximum stress is optimized. According to the knowledge of engineering mechanics, increasing the radius of the arc is an effective method to reduce stress concentration and improve safety. Therefore, this paper increases the radius of the cylinder arc transition and performs finite element analysis and equivalent linearity in turn. Processing. The calculated results are shown in Figure 4:
Figure 4 Effect of Arc Radius on Stress

It can be seen from Fig. 4 that increasing the radius of the arc can effectively reduce the stress at the arc transition of the oxygen cylinder, and the film stress, bending stress and total stress decrease with the increase of the radius of the arc.

4. Conclusion

Gas packaging containers are widely used in machinery, chemical, metallurgy, aerospace, medical and health, and daily life of residents. In this paper, ANSYS Workbench is used to analyze the typical gas packaging container-40L industrial oxygen cylinder, and the equivalent linearization method is used to optimize the cylinder structure, which significantly improves the safety of the cylinder transportation process. The packaging container structure optimization problem provides ideas. However, it should be pointed out that the analysis results have certain limitations due to the simplified handling of the cylinder structure during the analysis.

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