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Optimization of High-Pressure Gas Cylinder Design Using Aluminum Alloy and Fiber Winding Technology Under High Temperature Conditions

Song HUANG[a,b,c], Jie CHEN[a,b,1], Ziqiang HE[a], Xiuquan LI[a,b], Zongshan LI[a], Longyi ZHANG[a]
[a] *Key Laboratory of Electromechanical Equipment Security in Western Complex Environment for State Market Regulation, Chongqing Special Equipment Inspection and Research Institute, Chongqing 401121, China*
[b] *National Compress Natural Gas Cylinder Quality Supervision and Inspection Centre, Chongqing 401121, China*
[c] *Chongqing Academy of Metrology and Quality Inspection, Chongqing 401121, China*

Abstract. Given the weight and corrosion resistance limitations of traditional steel gas cylinders, this study proposes the use of lightweight, high-strength, and corrosion-resistant aluminum alloy as an alternative material. The research specifically focuses on analyzing the impact of winding technology and materials on the stress and strain of the gas cylinder at different temperatures (600°C) and pressures (from 15Mpa to 22.5Mpa), with the aim of optimizing the design and manufacturing process of the gas cylinder to meet more stringent engineering requirements. The study indicates that under high temperature (600°C) and high pressure (15Mpa) conditions, Type B gas cylinders exhibit lower average equivalent stress (573.66Mpa) and average stress intensity (589.36Mpa) compared to Types A and C. The average deformation is 0.01313m/m, slightly higher than that of Type C, but overall, Type B performs better. When the gas cylinder's volume increases, the average equivalent stress, stress intensity, and equivalent elastic strain all decrease, albeit with relatively minor overall changes. When the temperature rises to 1000°C, the average equivalent stress reaches 927.96Mpa, reflecting the impact of temperature on material expansion and internal stress. These findings are of significant practical importance for guiding the future design and manufacturing of high-pressure gas cylinders to meet higher performance and safety requirements.

Keywords. Fiber winding, aluminum alloy, high pressure gas cylinder, high temperature, stress analysis.

1. Introduction

In modern industries and militaries, high-pressure air cylinders, vital for gas storage, see widespread use in diving, aerospace, weaponry, and manufacturing. With the

[1] Corresponding Author, Jie CHEN, Key Laboratory of Electromechanical Equipment Security in Western Complex Environment for State Market Regulation, Chongqing Special Equipment Inspection and Research Institute; National Compress Natural Gas Cylinder Quality Supervision and Inspection Centre, China; Email: chenjie@cqtj.org

development of technology and the increase of application requirements, higher requirements have been put forward for the design, material selection, manufacturing process and safety performance of high-pressure air cylinders [1-3]. The design of high-pressure air cylinders not only needs to meet the specific working pressure and volume requirements, but also to ensure the reliability and safety in extreme environments. Traditional steel high-pressure air cylinders are gradually failing to meet the demands of modern applications due to disadvantages such as high weight and poor corrosion resistance. As a result, researchers have begun to explore the use of aluminum alloys, which are lightweight, high-strength and have good corrosion resistance, to manufacture high-pressure air cylinders. Aluminum alloy highlights its application advantages in the manufacture of high-pressure air cylinders with its light weight, economy, excellent processing performance and good corrosion resistance. Fiber-wound composite gas cylinders [4-6] usually consist of a thin metal liner of resin-based fiber-reinforced composite material with a certain thickness.

Researchers have investigated the effects of autofrettage on the performance of aluminum alloy liners and composite gas cylinders. Onder A et al. [7] conducted research on the burst pressure of filament-wound composite pressure vessels under the action of pure internal pressure variation, and compared the finite element analysis results with the analytical solutions provided by the commercial software ANSYS 10.0 and the experimental results, showing a high degree of consistency. Rafiee R et al. [8] estimated the burst pressure of filament-wound composite pressure vessels using dual-scale and multi-scale analysis methods. Enqi W et al. [9] showed that at the optimum autofrettage pressure, the liner's load capacity and fatigue life improved by 74% and 12 times, respectively, under working and fatigue loads. Hu [10] and Zhang [11] determined the autofrettage pressure for carbon fiber-wound hydrogen vessels using FE analysis, predicting material failure.

This study focuses on the effects of winding techniques and materials on the stresses and strains in high pressure gas cylinders under different temperature and pressure conditions. Through these studies, we aim to optimize the design and manufacturing process of gas cylinders to meet the increasingly stringent engineering requirements.

2. Modeling and Simulation Methods

This study utilized the Ansys Workbench software to construct a finite element analysis model for a composite pressure vessel. As shown in figure 1, the gas cylinder is composed of multiple layers of materials, including: Part 1, a glass fiber reinforcement layer with a thickness of 0.88 millimeters, Part 2, a carbon fiber reinforcement layer designed to enhance structural strength, with a thickness of 4.25 millimeters, and Part 3, the inner liner, made of aluminum alloy and stainless steel materials, with specific dimensions as depicted in figure 2. The research encompasses three types of gas cylinders, namely: Type A, a basic aluminum alloy cylinder, Type B, a fiber-wound aluminum alloy cylinder, and Type C, a fiber-wound stainless steel cylinder. For gas cylinders of different volumes, the head part remains constant, while the straight section is extended accordingly, with specific dimensional variations listed in table 1. The mechanical parameters of each material are shown in table 2.

Figure 1. Physical model

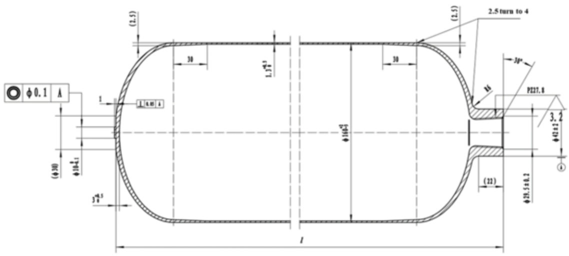

Figure 2. Liner size chart

In the study, finite element analysis was conducted using Ansys Workbench to simulate the physical scenario. The bottle's opening and base were designated as rigidly supported boundaries, with both pressure and temperature forces being applied. The interaction among the layered materials was modeled as a three-node contact element, representing surface-to-face contact.

Table 1. The mechanical parameters of each material

Volume	*l*
8L	487
10L	578
15L	837

Table 2. The mechanical parameters of each material

Material	Density (kg/m3)	0	Poisson's ratio	Bulk modulus (pa)	Shear modulus (pa)
Aluminum, 6061, T6	2713	6.9e10	0.33	6.8e10	2.6e10
Carbon fiber	1800	2.9e11	0.2	/	9.0e10
E-Glass	2600	7.3e10	0.22	4.3e10	3.0e10
1Cr18Ni9Ti	7930	1.9e11	0.3	1.6e11	7.5e10

3. Results and Discussion

By comparative analysis through table 3, figures 3-5 provide a detailed comparison of the mechanical properties of high-pressure gas cylinders made of different materials under high temperature (600°C) and high pressure (15Mpa) conditions. Through comparative analysis, we can observe that the average deformation of the Type B high-pressure gas cylinder is 0.01313m/m, which is slightly higher than that of the Type C cylinder at 0.0076159m/m. However, the Type B cylinder shows significant advantages in other key mechanical performance indicators. Specifically, the maximum equivalent stress and stress intensity of the Type B cylinder are significantly lower than those of the Type A and Type C cylinders, indicating that under the same operating conditions, the

Type B cylinder has a lower risk of failure and higher safety performance.Furthermore, the average stress intensity of the Type B cylinder is 589.36Mpa, which is not only lower than that of the Type A cylinder at 929.66Mpa, but also lower than that of the Type C cylinder at 615.77Mpa. A lower stress intensity means that the material is less likely to undergo plastic deformation or failure under the same external force, thus providing higher reliability and durability. Given the superior performance of Type B gas cylinders under high-temperature, high-pressure conditions, with lower stress intensity and deformation, this study will focus on Type B for further research. We'll examine how varying design and manufacturing factors affect its performance and safety, aiming to optimize these for improved cylinder reliability.

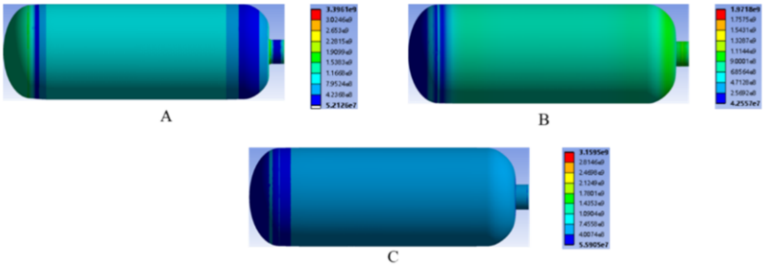

Figure 3. Von mises stress of different type pressure cylinder

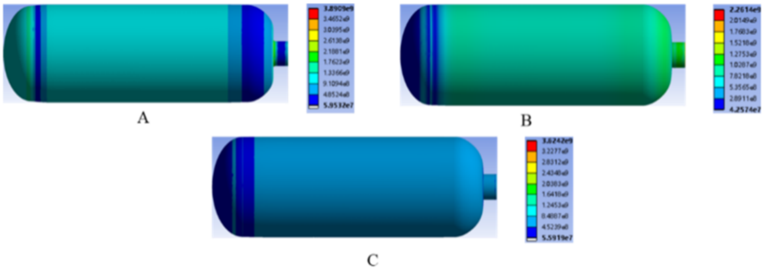

Figure 4. Stress intensity of different type pressure cylinder

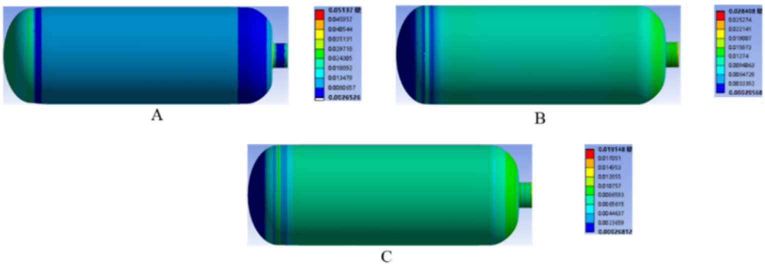

Figure 5. Equivalent elastic strain of different type pressure cylinder

Table 3. The strain and stress conditions of different types of gas cylinders.

Type	Temperature (℃)	Pressure (Mpa)	Average Von mises stress (Mpa)	Average stress intensity (Mpa)	Average equivalent elastic strain (m/m)
A	600	15	864.69	929.66Mpa	0.012862
B	600	15	573.66	589.36Mpa	0.01313m/m
C	600	15	566.12	615.77Mpa	0.0076159m/m

Figures 6-8 present a comparison of the mechanical properties of Type B high-pressure gas cylinders with varying volumes under the conditions of a constant temperature (600°C) and pressure (15Mpa). The data reveal the influence of cylinder volume on equivalent stress, stress intensity, and equivalent elastic strain. With an increase in the volume of the gas cylinder, there is a noticeable upward trend in the maximum equivalent stress, maximum stress intensity, and maximum equivalent elastic strain. This trend may be attributed to the fact that at a larger volume, the material must withstand greater volumetric changes under the same pressure, which can lead to an increase in stress values in areas of stress concentration. However, in contrast to the increasing trend observed in the maximum values, the average equivalent stress, average stress intensity, and average equivalent elastic strain of the cylinders decrease as the volume increases. Specifically, the average equivalent stress has dropped from 573.66Mpa to 488.56Mpa, the average stress intensity from 637.60Mpa to 536.90Mpa, and the average equivalent elastic strain from 0.01313m/m to 0.011838m/m. This decrease can be explained by the increase in the material's surface area, as the volume increases, so does the surface area, which results in a more uniform distribution of stress and strain, thereby reducing the average values.

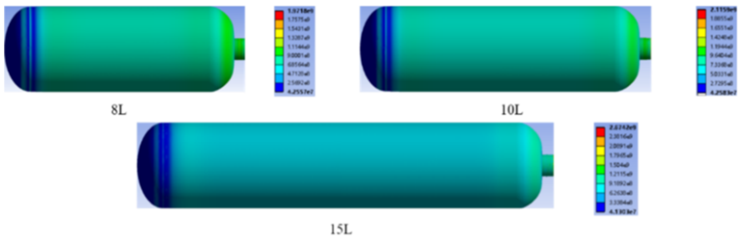

Figure 6. Von mises stress of different type pressure cylinder

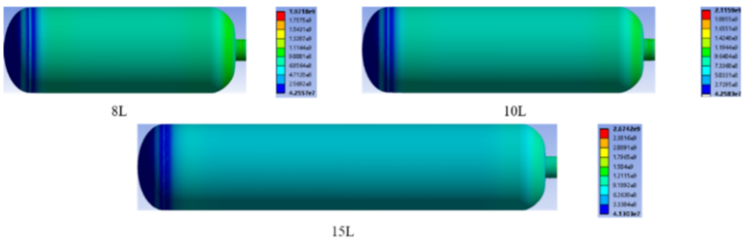

Figure 7. Stress intensity of different type pressure cylinder

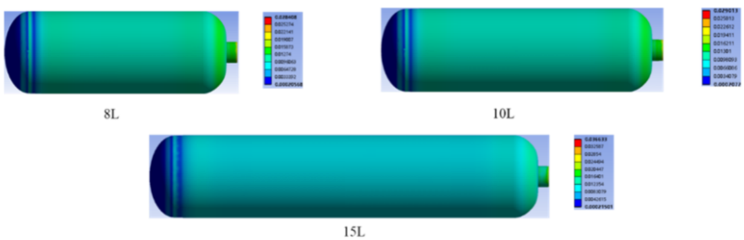

Figure 8. Equivalent elastic strain of different type pressure cylinder

Figures 9-11 detail the changes in the mechanical properties of a Type B high-pressure gas cylinder under a fixed volume (8L) and high temperature (600°C) conditions across various pressures. Table 4 presents the specific results. The data clearly demonstrate the significant impact of pressure on the cylinder's performance. As the working pressure increases, the maximum equivalent stress, maximum stress intensity, and maximum equivalent elastic strain all show a clear upward trend. This suggests that under higher working pressures, the internal stress state of the material is more severe, which could lead to a reduction in the material's fatigue life and an increased risk of failure. It is noteworthy that, despite the increase in maximum values with pressure, the minimum stress intensity has actually decreased. This could be due to the stress distribution within the material becoming more uneven under high-pressure conditions, leading to the occurrence of localized stress concentrations. At a pressure of 15Mpa, the average equivalent stress, average stress intensity, and average equivalent elastic strain of the Type B cylinder are 573.66Mpa, 637.60Mpa, and 0.01313m/m, respectively. When the pressure is increased to 22.5Mpa, these average values rise to 669.44Mpa, 685.47Mpa, and 0.012569m/m, respectively.

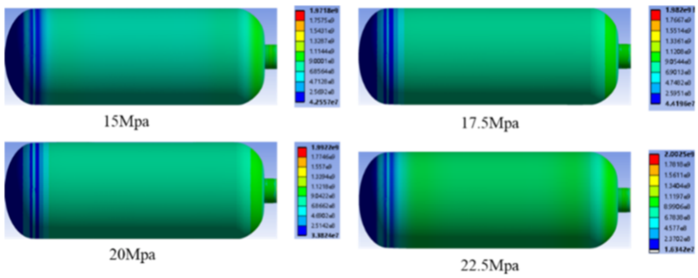

Figure 9. Von mises stress of B pressure cylinder under different pressure

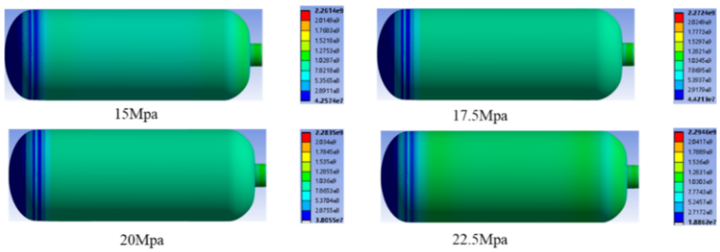

Figure 10. Stress intensity of B pressure cylinder under different pressure

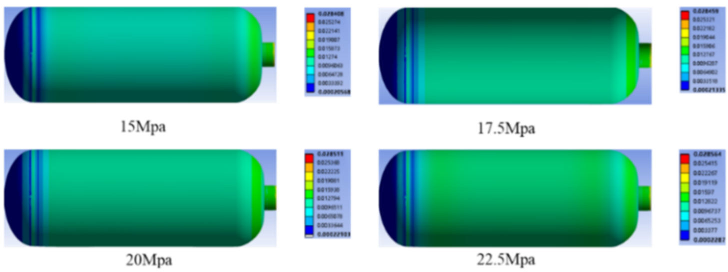

Figure 11. Equivalent elastic strain of B pressure cylinder under different pressure

Table 4. The strain and stress conditions of different pressure

Temperature (°C)	Pressure (Mpa)	Average Von mises stress (Mpa)	Average stress intensity (Mpa)	Average equivalent elastic strain (m/m)
600	15	573.66Mpa	637.60Mpa	0.01313m/m
600	17.5	589.36Mpa	6.5348e8	1.1724e-2
600	20	6.0561e8	669.44Mpa	1.2143e-2
600	22.5	669.44Mpa	685.47Mpa	0.012569m/m

Figures 12-14 display the variations in equivalent stress, stress intensity, and equivalent elastic strain of Type B high-pressure gas cylinders under fixed volume (8L) and pressure (17.5Mpa) conditions at different temperatures. Table 5 provides the strain and stress conditions of different pressures. The observations indicate that as the temperature increases, the equivalent stress, stress intensity, and equivalent elastic strain of the gas cylinder all show an upward trend. This phenomenon can be attributed to the thermal expansion of materials caused by the rise in temperature, especially under constrained conditions, where thermal expansion may lead to a significant increase in internal stress. Specifically, when the temperature gradually increases from 600°C to 1000°C, the average equivalent stress of the gas cylinder increases from 589.36Mpa to 927.96Mpa, the average stress intensity increases from 653.48Mpa to 1034.60Mpa, and the average equivalent elastic strain rises from 0.011724m/m to 0.017958m/m. This suggests that under the combined effects of high temperature and high pressure, the mechanical properties of the material may be significantly affected, which needs to be fully considered in the design and use process.

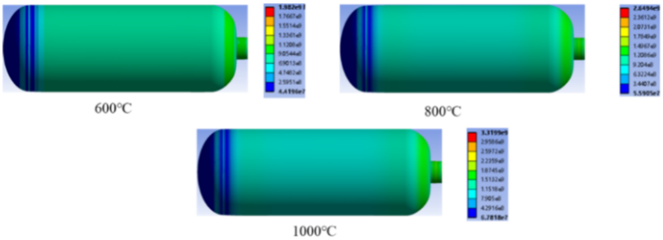

Figure 12. Von mises stress of B pressure cylinder under different temperature

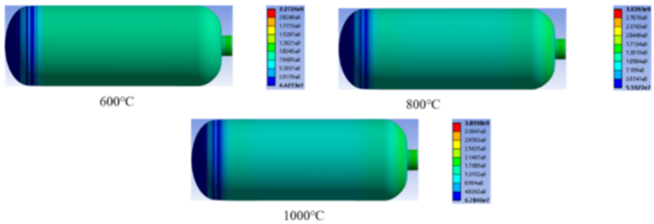

Figure 13. Stress intensity of B pressure cylinder under different temperature

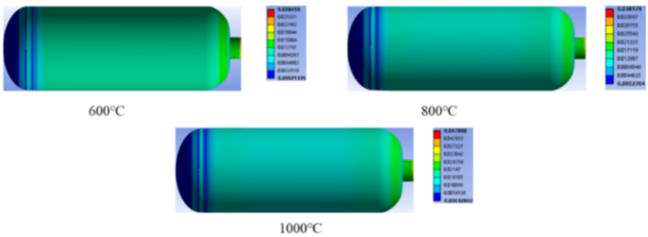

Figure 14. Equivalent elastic strain of B pressure cylinder under different temperature

Table 5. The strain and stress conditions of different pressure

Temperature (°C)	Pressure (Mpa)	Average Von mises stress (Mpa)	Average stress intensity (Mpa)	Average equivalent elastic strain (m/m)
600	17.5	589.36	653.48	0.011724
800	17.5	757.56	843.39	0.014825
1000	17.5	927.96	1034.60	0.017958

4. Conclusion

By comparing the performance of high-pressure gas cylinders made of different materials under high temperature and high pressure conditions, this study selected the Type B high-pressure gas cylinder for in-depth research. The conclusions of the study are as follows:

1. Under high temperature (600°C) and high pressure (15Mpa) conditions, the Type B high-pressure gas cylinder exhibits lower average equivalent stress and stress intensity compared to gas cylinders made of other materials.
2. An increase in volume helps to reduce the stress levels of the gas cylinder under the same conditions.
3. A rise in temperature causes the material to expand, which may lead to an increase in internal stress.

The findings of this study are instrumental in guiding the future optimization of high-pressure gas cylinder design and manufacturing to meet higher standards of performance and safety.

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