Numerical simulation and research of the split ultrahigh pressure cylinder

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Abstract. The pressure capacity of an ultrahigh pressure cylinder is the bottleneck of the development of ultrahigh pressure vessels. In order to improve the pressure capacity of the cylinder, the finite element software was used to analyse the single-layer thick-walled cylinder and the split cylinder under the same load. Research results show that the split cylinder has higher pressure capacity than that of single-layer thick-walled cylinder. Simulation of the different number subsections of the same size split cylinder show that the number’s increase of the subsections can effectively reduce their Von Mises stress under the same load.

1. Introduction
The development of ultrahigh pressure technology is constantly refreshing new pressure levels. Traditional single-layer thick-walled cylindrical ultrahigh pressure vessel will produce tremendous stress on the inner wall of the cylinder under working load. Moreover, the stress distribution along its radial direction is extremely nonuniform, which will greatly affect the pressure capacity of the cylinder. However, the stress distribution will be more and more nonuniform and the utilization of the material will be reduced just by increasing the size of the cylinder [1].

Based on the principle of divided before cracking[2], the sector block of cemented carbide was added to the inside of the new type ultrahigh pressure cylinder. Besides reducing the difficulty of sintering the whole hard alloy cylinder [3], the split block may generate no tangential stress under load and can transfer the load to the outer cylinder, which will generate radial stress and tangential stress in the outer cylinder [4]. Therefore, the ultra-high pressure structure with split cylinder will be widely used in the future.

2. Design Method of the Cylinder Body
Traditional ultrahigh pressure cylinder body is mainly a forged single-layer thick-wall cylinder, as shown in Fig 1 (a).

In order to improve the pressure capacity of ultrahigh pressure vessels, according to the idea of divided before cracking, the interior cylinder is evenly divided into four subsections along its radial direction. The split cylinder body is shown in Fig 1 (b).

The split cylinder does not produce tangential stress under working load, and its radial stress will be transferred outward along the split block. As the stresses transferring to the outer cylinder, their values will be greatly reduced. This is not available in a single-layer thick-walled cylinder. Therefore, the split cylinder can effectively improve the stress distribution state of the ultrahigh pressure cylinder, reduce the local stress, and thus improve the working time of the ultra-high pressure cylinder.
3. Construction of Finite Element Model

The working pressure $P_b$ of the ultrahigh pressure cylinder in a factory is 800MPa. According to the actual design requirements, the inner diameter $D_b$ of the cylinder is determined as 600mm, the outer diameter $D_0$ is 1800mm, and the length of the cylinder body $L$ is 1000mm. According to the Minimum Shear Stress Criterion of the design principle of a split cylinder, the outside radius $r_c$ of the split block is set to 600mm.

In order to research the pressure capacity of several ultrahigh pressure cylinders, the finite elements software ANSYS Workbench was used to the stress distribution under the working pressure $P_b$ on the inner wall of the split block. The material of the outer cylinder is 45CrNiMoVA, and the split block is YG8 cemented carbide. The properties of the two materials are shown in Table 1.

**Table 1.** Material Parameters of 45CrNiMoVA.

| Yield Strength (MPa) | Ultimate Strength (MPa) | Modulus of Elasticity (GPa) | Poisson's Ratio | Shear Strength (MPa) |
|----------------------|-------------------------|----------------------------|-----------------|----------------------|
| 1330                 | 1470                    | 213                        | 0.21            | 768                  |

**Table 2.** Material Parameters of YG8.

| Ultimate Strength (MPa) | Modulus of Elasticity (GPa) | Poisson's Ratio | Shear Strength (MPa) |
|-------------------------|-----------------------------|-----------------|----------------------|
| 6200                    | 213                         | 0.21            | 3250                 |

In addition, according to the stress characteristics of the cylinder, both cylinders can be simplified as the plane strain problem to study. In the calculation process, the isotropic linear elastic material model is used for both materials. For the contact setting, the augmented Lagrange algorithm is adopted, and the friction coefficient between the outer wall of the split block and the inner wall of the outer tube is 0.2. The load set on the inner wall of the split block is 800MPa. Considering the calculation of the contact part of the cylinder with the split block, the mesh of this area is refined. The finally finite element model is shown in Fig 2.

![Finite element model of different cylinder](image)

**Figure 2.** Finite element model of different cylinder
4. Analyses of Cylinder Stress

Fig 3 shows the cloud diagram of Von Mises stress distribution of the two types of cylinder as $P_b$ is set to 800MPa. The maximum values of the two different structures are 1098.4MPa and 884.13MPa respectively. And the maximum values are focused on the inner wall of the cylinder. The results show that the Von Mises stress value of single-layer thick-walled cylinder is much larger than that of the split cylinder. The maximum Von Mises stress of the split cylinder decreased 19.5% compared with that of the single-layer thick-walled cylinder.

According to the Maximum Distortion Energy Criterion, the Von Mises stress of the single-layer thick-walled cylinder is much close to the material yield strength of 45CrNiMoVA under the working pressure of 800MPa. If the working pressure increases, the inner wall of the single-layer thick-walled cylinder would soon produce plastic deformation and result in failure. The Von Mises stress of the split cylinder is much less than the yield strength of the material, so the split cylinder can bear higher working pressure.

![Cloud diagram of Von Mises stress distribution in cylinder](image1)

Figure 3. Cloud diagram of Von Mises stress distribution in cylinder

The cloud diagram of the maximum shear stress distribution of the two types of cylinder is shown in Fig 4. The maximum values of the two type cylinder are 632.88MPa and 474.79MPa respectively. Compared with the single-layer thick-walled cylinder, the maximum shear stress of the split cylinder is reduced 25.0%. The shear strength of 45CrNiMoVA and YG8 are 768MPa and 3250MPa respectively. According to the Maximum Shear Stress Criterion, the maximum shear stress of the single-layer thick-walled cylinder is close to the shear strength of the material under the working stress. And the maximum shear stress of the split cylinder in the cloud diagram is far less than the shear strength of YG8.

Based on the above results, the split cylinder has remarkably higher working pressure capacity according to both the Maximum Distortion Energy Criterion and the Maximum Shear Stress Criterion.

5. Study on Split Cylinder

In order to obtain the law of the split cylinder number which effects on the pressure capacity, numerical simulations with four, six, eight, ten and twelve subsections are done in this section. The Von Mises and maximum shear stress cloud diagrams are shown in Fig 5 and Fig 6, respectively.
Based on the Von Mises stress and maximum shear stress distribution, the stress line charts obtained from the collected data is shown in Fig 7.

Figure 7. Two types stress line charts
Under the same conditions, the working pressure of 800MPa is applied to the inner wall of the cylinder, the cloud diagram of the Von Mises stress distribution of the five kinds of cylinders are shown in Fig 5. The maximum Von Mises stress of the four, six, eight, ten and twelve-subsection cylinder are 884.13MPa, 750.93MPa, 739.89MPa, 739.63MPa and 738.58MPa, respectively.

According to the Fig 7, the maximum Von Mises stresses of the cylinders are decreased 15.1%, 16.3%, 16.4% and 16.5% respectively with the number of the subsections increasing from 4 to 12. The areas of stress concentration are also decreased with the increase of the number of the subsection. Compared with the other four split cylinder, the twelve-subsection cylinder has better pressure capacity.

Fig 6 shows that the cloud diagrams of the distribution of the maximum shear stress for the five kinds of cylinders are 474.79MPa, 413.89MPa, 406.33MPa, 406.97MPa and 407.24MPa respectively. Obviously, the maximum shear stress of the five kinds of split cylinders is less than the shear strength of YG8. And the twelve-subsection cylinder has the minimum shear stress.

As shown in Fig 7, the maximum shear stress decreased 12.8%, 14.4%, 14.3% and 14.2% respectively as the subsections number increasing from 4 to 12. The area of stress concentration also decreases with the increasing of the number of subsection.

The results above show that the twelve-subsection cylinder has better pressure capacity than the other four cylinders.

6. Conclusions
(1) By numerical simulation of the single-layer thick-walled cylinder and the split cylinder under the same condition, the Von Mises stress and maximum shear stress of the single-layer thick-walled cylinder are 19.5% and 25.0% larger than that of the split cylinder respectively.

(2) Compared with the four-subsection split cylinder, the Von Mises stress and maximum shear stress of the twelve-subsection split cylinder were reduced 16.5% and 14.2% respectively under the same condition. Therefore, more subsection of the cylinder will have the higher pressure capacity.

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