Thermodynamic study on complex parts of the sphere and ellipsoid of a nuclear explosive device

GOU ZHENZHI[a,b*]
HE BIN[a]
YANG GUILIN[a]

[a] Xiñan High Technology Institute , Xiñan, 710025, China

[b] Troops number 96421, Baoji, 721012, China

Abstract   Because the heat release of plutonium material, the composite structure is heated and the stress and strain of the composite structure will increase, which will affect the thermodynamic properties of the structure. The thermodynamic analysis of complex structures, which are composed of concentric structures of plutonium, beryllium, tungsten, explosives, and steel, was carried out. The results showed that when the structure is spherical, the temperature is higher than that of the ellipsoid structure. Stress of the elliptical structure is greater than the spherical structure. This study showed that the more flat the shell is, the greater the stress concentration point occurs at the long axis, and the maximum stress occurs at the beryllium layer. These conclusions provide theoretical support for the plutonium composite component testing.

Keywords: Plutonium component; Thermodynamic analysis; Numerical simulation; Temperature field; Stress field

1   Introduction

The plutonium element in nuclear explosive device is a radioactive element, which emits a large amount of energy in the radioactive decay and fission process. Nuclear explosive devices, as the most important part of nuclear

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*Corresponding Author. E-mail: zhenzhi3644@163.com

weapon, must be guaranteed by good mechanical performance index, which
is the basis of the deterrent force. Therefore, it is necessary to analyze ther-
mal effect of nuclear explosive device, and to determine its thermodynamic
properties. In order to study the effect of thermal stress on the mechanical
properties of the whole device, the nuclear explosive device, which is com-
monly used in academic research, in many papers and webs [1,3] has been
considered.

In 1995, Zhao Ru calculated nitrogen temperature is 77 K under the
condition of safe removal of nuclear warheads [5]. In 2005 Xiao Gang sim-
ulated thermal coupling calculation of the open model of nuclear device,
and conclusions show the highest temperature of the primary structure can
reach 390 K in the ideal state [4]. Gao Zhengming considered that the
Steven model can not exist in engineering field because the heat stress is
too high [2]. There is no research on the complex ellipsoid structure with
plutonium layer.

The schematic diagram of nuclear explosive device is shown in Figs. 1
and 2, and structure layout is obtained and simplified according to the in-
ner data. The device parts from inside to outside in turn are plutonium,
beryllium, tungsten, explosives, and steel. In order to analyze the effect
of thermal stress on the device of different shapes, the three kinds of de-
vices have been analysed, which are: spherical shell the same thickness but
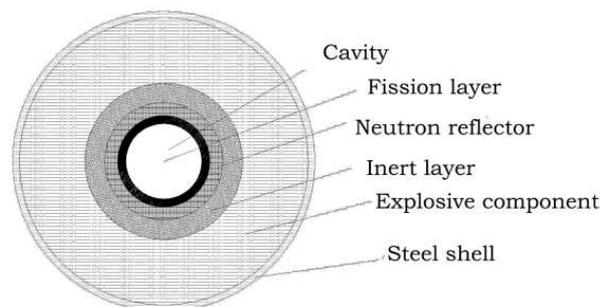elliptical shell, and the different thickness of elliptical shell.

Figure 1: Schematic diagram of complicated multiplelayer components.

Figure 2: Schematic diagram of W88 nuclear explosive device.

2 Thermodynamic analysis of a spherical model

For arbitrary time and material, the heat conduction partial differential equation is

$$\frac{\partial}{\partial x}\Big(\lambda_{xx}\frac{\partial T}{\partial x}\Big) + \frac{\partial}{\partial y}\Big(\lambda_{yy}\frac{\partial T}{\partial y}\Big) + \frac{\partial}{\partial z}\Big(\lambda_{zz}\frac{\partial T}{\partial z}\Big) + q_v = \rho c\frac{\partial T}{\partial t} \ , \qquad (1)$$

where q_v is the thermal strength of solution, T – temperature field distribution function, t – time, λ_{xx}, λ_{yy}, λ_{zz} – coefficients of thermal conductivity along X, Y, and Z direction, ρ and c – density and thermal conductivity of material respectively, and x, y, z are the Cartesian coordinates.

When ρ, c, and λ are constant, the formula can be simplified as [6]

$$a\Big(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\Big) + \frac{q_v}{\rho c} = \frac{\partial T}{\partial t} \ . \qquad (2)$$

where $a = \frac{\lambda}{\rho c}$ is the temperature or diffusion coefficient.

The boundary conditions of the first kind are embodied in the heat exchange from the external temperature field to internal one. Knowing boundary temperature value can obtain the solution of internal heat equation [8]

$$\lambda\frac{\partial T}{\partial x}n_x + \lambda\frac{\partial T}{\partial y}n_y + \lambda\frac{\partial T}{\partial z}n_z = T_s(x, y, z, t) \ ,$$

where n_x, n_y and n_z are the cosine functions in the direction of boundary, and T_s denotes temperature on the surface of the object.

Thermodynamic properties of the component material and spherical structure size are given in Tabs. 1 and 2, respectively. Spherical structure model and its computational grid division is shown in Fig. 4 and in Tab. 2. The steel shell is in contact with air, and heat convection coefficient is 5 W/m^2. The decay power of the plutonium material with time is shown in Fig. 3, whereas decay heat power is about 0.001857–0.001863 W/kg. Therefore, decay power can be approximately taken as 4.0×10^5 W/mm^3. The outer surface of steel shell is fixed. Elliptical shell is thickness uniform and thickness ratio along the long and short axis direction is 2:1.

The simulation of the nuclear explosive device using a computational thermodynamic model enable high-quality analysis of main parameters that effect on device features, providing realistic estimation of the decisive factors. Temperature distribution for the spherical structure is shown in Fig. 5.

Table 1: Thermodynamic parameters of complex parts.

Material	Thermal conductivity	Density (kg/m^3)	Specific heat (J/kg K)	Modulus of elasticity (GPa)	Poisson's ratio	Expansion coefficient (10^6/K)
Plutonium [4]	27.6	18950	113	100	0.22	12.55
Beryllium [5]	188.3	1848	1883	411	0.07	1.3
Wolfram [5]	145	19260	134	5800	0.28	4.45
Explosive [5]	0.64	1670	690	5.8	0.34	7
Steel [5]	16.3	7850	502.4	210	0.30	17

Table 2: Spherical component size parameter.

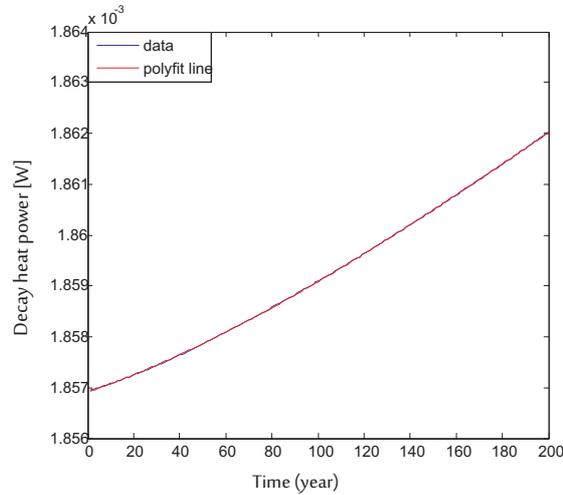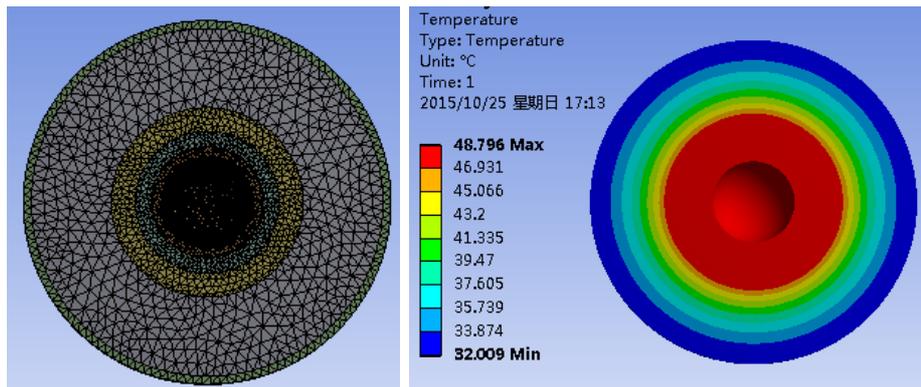| Spherical shell size	Layer				
	Plutonium	Beryllium	Tungsten	Explosive	Steel
Inner radius	57.7	70	90	120	220
Outer radius	70	90	120	220	230
Thickness	12.3	20	30	100	10

Figure 3: Plutonium decay power.

Figure 4: Grid division. Figure 5: Temperature contour.

As can be seen from Figs. 6 and 7, the maximum heat flux is at the junction of plutonium and beryllium, and the maximum heat flux reached is 441.89 W/m². According to Fig. 6, it can be seen that the thermal conductivity of beryllium is 441.89 W/m², so the temperature difference of two surfaces is the largest, as well as the heat flux of plutonium and beryllium.

It can be seen in Figs. 8 and 9 that the equivalent elastic strain occurs on inner surface of the explosive and the tungsten, while the elastic strain of the tungsten material is the smallest. From Figs. 10 and 11, we can see
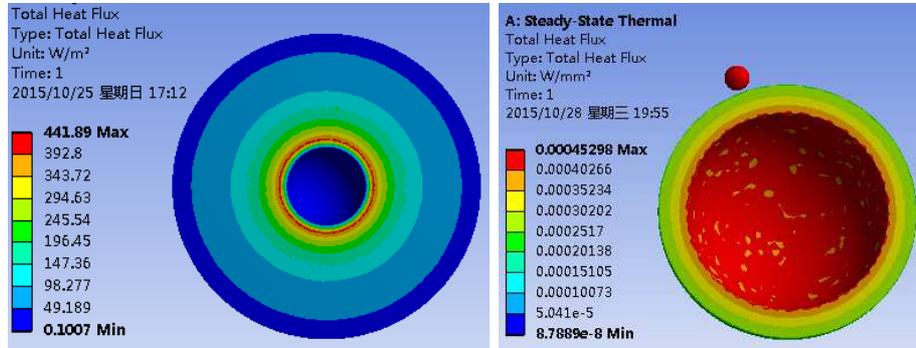
Figure 6: Heat flow density contour.

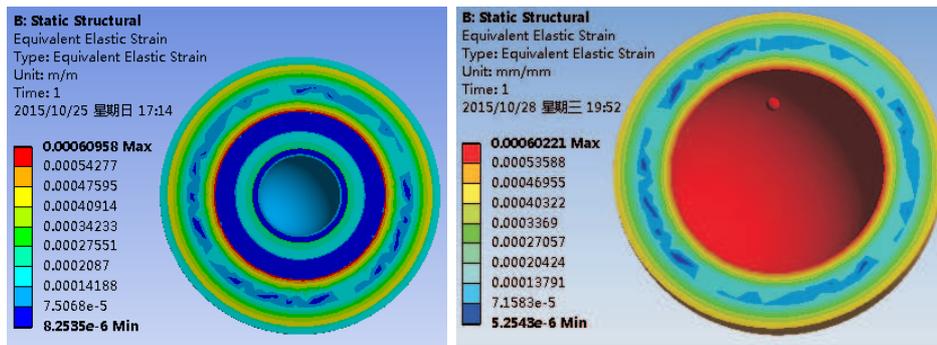Figure 7: Heat flow density contour of beryllium.

Figure 8: Equivalent elastic strain.

Figure 9: Equivalent strain contour of explosive.

that the stress of the inner surface of beryllium component and the outside surface of plutonium component reaches the maximum of 89 MPa. As can be seen from Fig. 12, the total maximum deformation locates at explosive part, while it shows that the total deformation of the steel shell is zero, because it is set into a steel shell as a fixed structure.
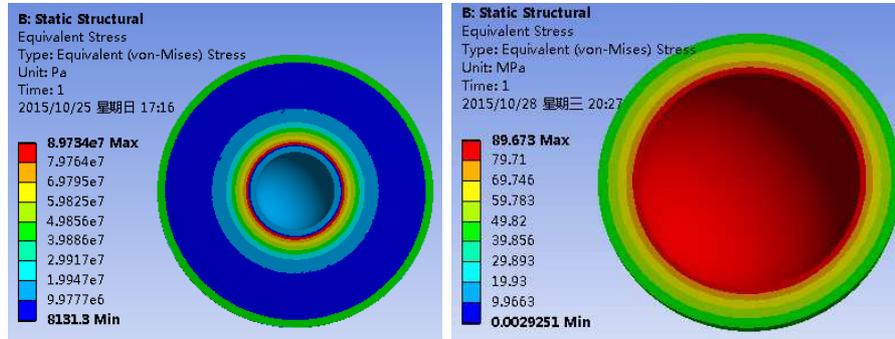
Figure 10: Equivalent stress contour.

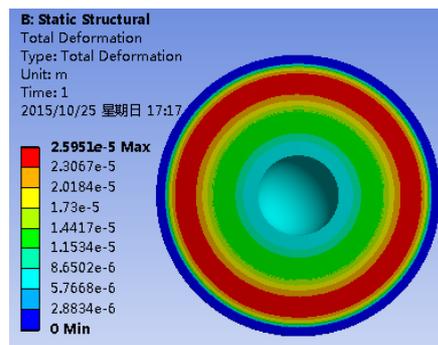Figure 11: Equivalent stress contour of beryllium.

Figure 12: Total deformation contour of sphere structure.

3 Thermodynamic analysis of the five ellipsoidal shells of the same thickness

Two hypotheses were proposed. The first that is the volume of each eliptical layer equal to the volume of the corresponding spherical shell. The second assumption is about the length ratios of the long and short axis of the plutonium shell equal to 2:1.

The volume of the ellipsoid layer is equal to the volume of the responding sphere,

$$V = 4\pi\Big[abc - (a-r)(b-r)(c-r)\Big]/3 = 4\pi(70^3 - 57.7^3)/3 \ ,$$

where a is x-axis length of outer surface of plutonium part, b is y-axis length of outer surface of plutonium part, and c is z-axis length of outer surface of plutonium part. According to the actual situation, make $b = c$ and $a/b = 2$, the following values were obtained: $a = 108.787$, $b = 54.394$, $c = 54.394$, and $r = 12.3$. The inner ellipse parameter of the plutonium shell material could be also obtained, which were 96.487, 42.094, 42.094, respectively. The structure of computational grid for elliptical case is shown in Fig. 13.

Table 3: The parameters of ellipsoid.

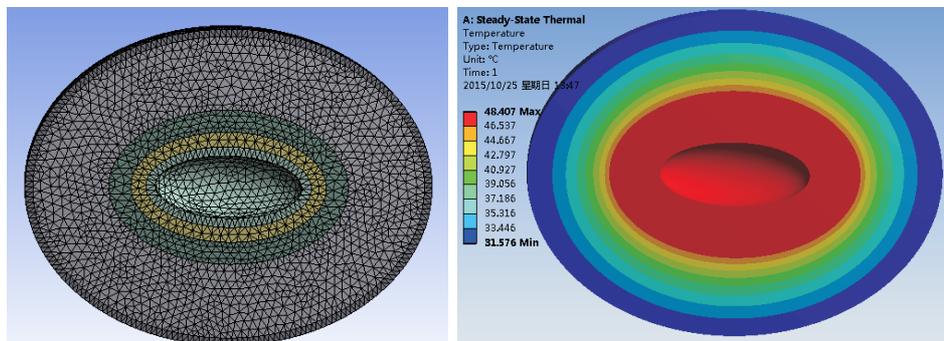| Spherical shell size, mm	Layer				
	Plutonium	Beryllium	Tungsten	Explosive	Steel
Inner short radius	42.094	54.394	74.1952	103.8556	203.1369
Inner long radius	96.487	108.787	128.5882	158.2486	257.5299
Outer short radius	54.394	74.1952	103.8556	203.1369	213.0911
Outer long radius	108.787	128.5882	158.2486	257.5299	267.4841
Thickness	12.3	19.8012	29.6604	99.2813	9.9542

Figure 13: Grid division and temperature stress contour of ellipsoid.

We can see (Fig. 13) that the maximum temperature of the elliptical component is 48.4107 °C, thus the highest temperature is lower than that of the spherical component, and is concentrated on the inner surface of the plutonium component.

It can be seen from Figs. 14 and 15 that the heat flux density of the beryllium component is the largest, and the heat flux is 480.9 W/m^2. The lowest heat flux density is on the inner surface of the steel component.
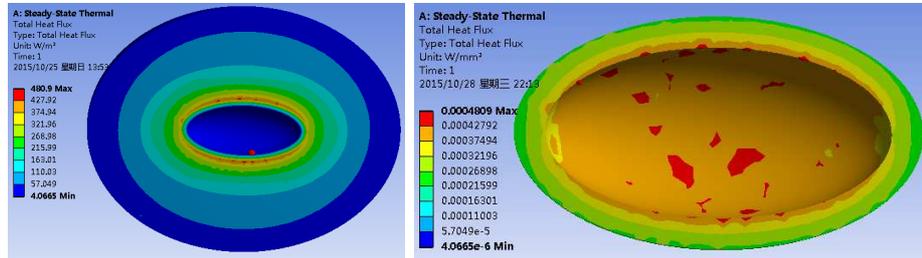
Figure 14: Heat flow density contour.

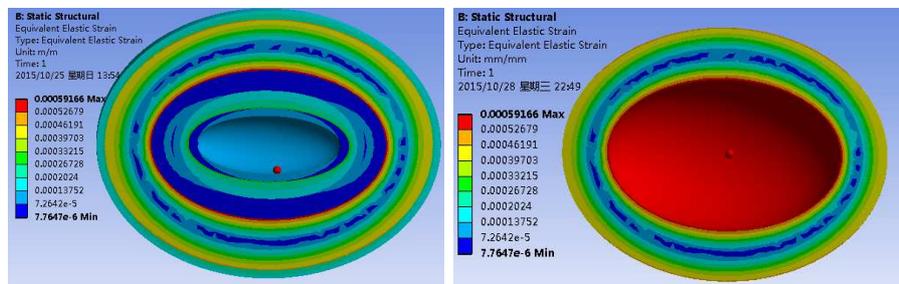Figure 15: Heat flow density contour of beryllium.

Figure 16: Equivalent elastic strain.

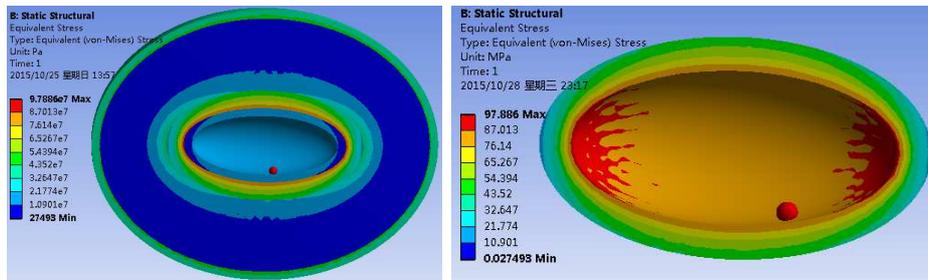Figure 17: Equivalent strain contour of explosive.

Figure 18: Equivalent stress contour.

Figure 19: Stress contour of beryllium component.

From Fig. 16 the etastic strain is on the outer surface of the tungsten component. The largest equivalent strain (see Fig. 17) is on the explosive parts, reaching the 5.9166×10^{-4} mm/mm. The maximum and minimum
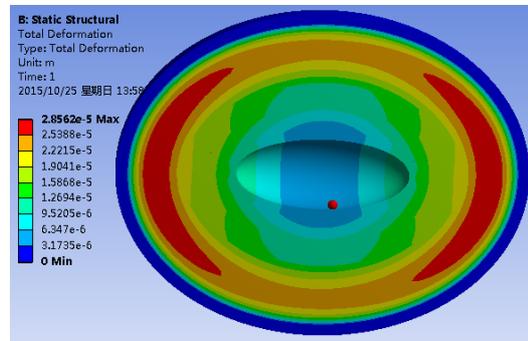
Figure 20: The total deformation contour of ellipsoid.

strain can easily occur at the junction surface of the two part. From the strain of the plutonium component, it can be seen that the lateral strain in the long axis bending part surface is small. From the total strain contour of elliptical part, the strain contour of the ellipse is not uniform along the radial direction. In the curvature surface, the strain changes have been occured. Figures 18 and 19 show that maximum stress is on the inner surface of beryllium element and the maximum stress is on the inner surface near the long axis. As can be seen from the total deformation contour (Fig. 20), the displacement deformation of the long axis of the explosive part is the largest, and the distribution is symmetric.

From previous research results, the internal temperature of the circular structure is $48\,^\circ$C, and the maximum temperature is $32\,^\circ$C, so the elliptical structure design can effectively reduce the internal temperature. According to the stress and strain contour, the maximum equivalent stress of spherical structure is 89.65 MPa, while the maximum stress of ellipsoidal structure is 94.3 MPa. When component section diameter size is infinite, elliptical structure tends to be a spherical structure. therefore, this design is not reasonable.

4   Ratio of long to short axial ellipsoidal shell equal to 2:1

We assume four hypotheses: first, the volume of each layer is equal to the previous two models; second, the ratio of long axis to the short axis is 2:1; third, the ratio of the long axis of the shell thickness to the short axis of

the shell thickness is 2:1; fourth, the length in Z direction is equal to that of Y direction. Thus, the ellipsoidal volume can be expressed as:

$$V = 4\pi(a_1 b_1^2 - a_2 b_2^2)/3 = 4\pi(R_1^3 - R_2^3)/3 \ ,$$

and $a_1/b_1 = 2$, $a_2/b_2 = 2$, where R_1 and R_2 are the long and short axis length, respectively.

Table 4: The calculation results.

| Spherical shell size, mm	Layer				
	Plutonium	Beryllium	Tungsten	Explosive	Steel
Inner short radius	45.7965	55.5590	71.4330	95.2441	174.6141
Inner long radius	91.5930	111.1181	142.8661	190.4881	349.2282
Outer short radius	55.5590	71.4330	95.2441	174.6141	182.5511
Outer long radius	111.1181	142.8661	190.4881	349.2282	365.1022
Long diameter thickness	19.5250	31.748	47.622	158.7401	15.874
Short diameter thickness	9.7625	15.874	23.8111	79.37	7.937
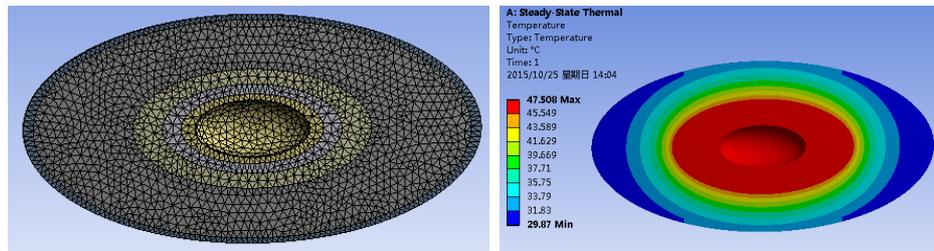
Figure 21: Grid division and temperature stress contour of ellipsoid.

As can be seen from Fig. 21, the maximum temperature occurs in the plutonium, beryllium, tungsten components. The temperature of the explosive components is not uniform, and the temperature gradient near the long axis part is higher than other part, meanwhile the distribution is symmetric. The temperature is lower than the maximum temperature of the previous two models. It shows this model has good cooling performance.

As previous two models, the maximum heat flux density occurs in the internal part of beryllium. It can be seen the maximum heat flux density is in the vicinity of the long axis of beryllium, which is not the same as the thickness of the uniform. In addition, the maximum heat flux is increased up to 532.5 W/m^2.
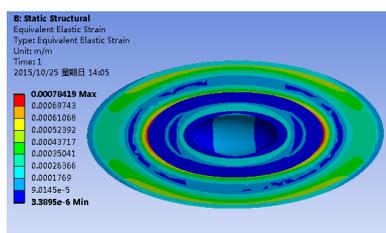

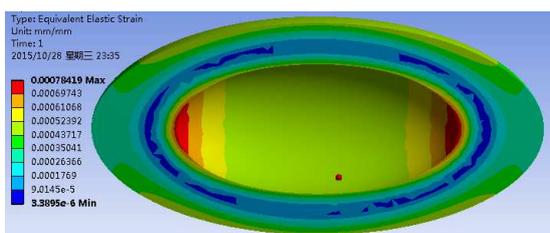Figure 22: Equivalent elastic strain diagram.

Figure 23: Elastic strain diagram of explosive parts.

The maximum strain can be seen from the strain diagrams (Figs. 22 and 23), which occurs on the inside surface of the long axis direction of the explosive component. This is because the elastic modulus of the explosive component is the smallest, but the Poisson's ratio is the largest. The strain on the outer side of the explosive element is smaller because the steel shell is set to a fixed model, which inhibits the development of the strain of the explosive component.
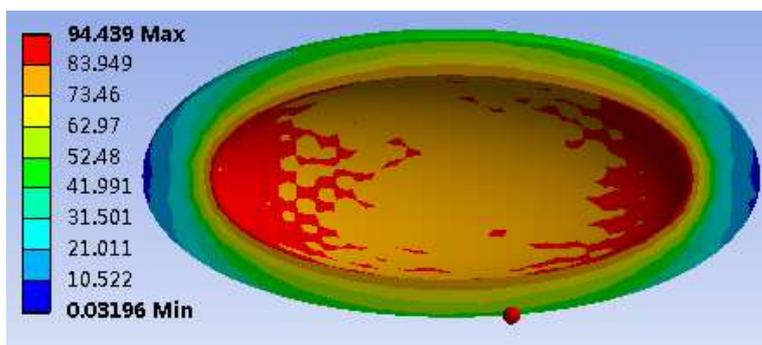

Figure 24: Stress contour of beryllium part.

The maximum stress appears on the inner part of the beryllium element, where its value is equal to 94.439 MPa. The maximum stress is lower than

the stress of the spherical shell, which shows that the shape of structure can effectively reduce the maximum stress value.
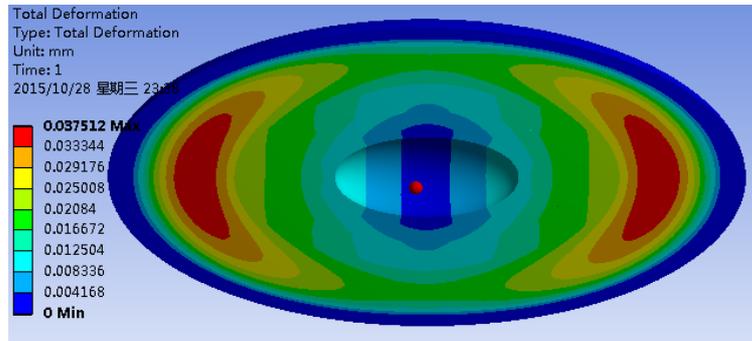

Figure 25: Total deformation of components

From Fig. 25, it can be seen that the maximum deformation of the element is near the long axis of explosive component, because the strain is the largest near the long axis of the explosive, and the thickness of the explosive is the largest. So the maximum deformation occurs on the long axis of the explosive part.
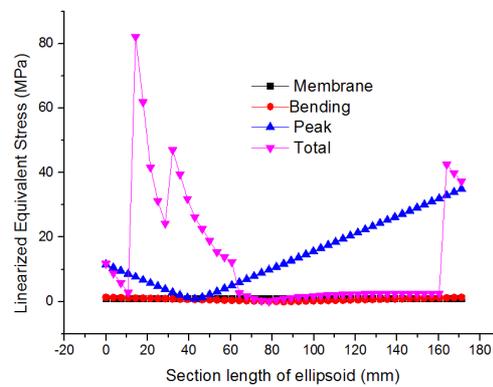

Figure 26: Four kinds of radial linear stress.

As can be seen from Fig. 22, the total equivalent stress occurs at the 13 mm from 1 to 2 point.while from 65 mm to 160 mm, the total equivalent stress is small, but at 170 mm position, the total stress value will suddenly increase. From Fig. 27, the total stress value is very small in the vicinity of explosive components.
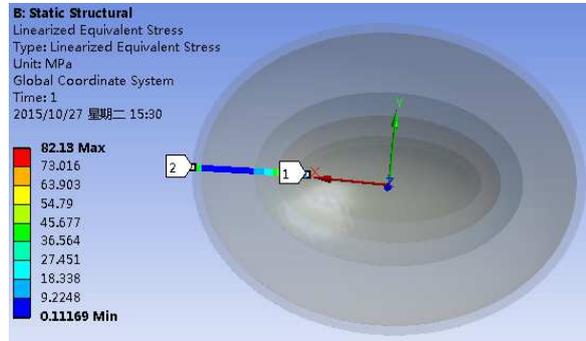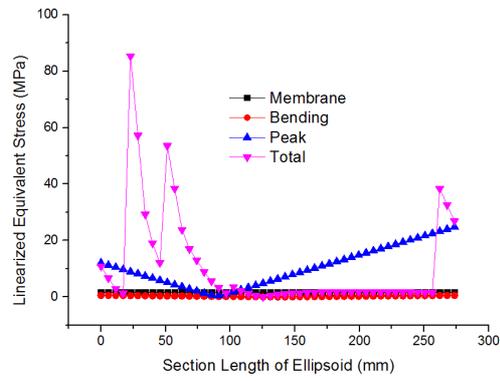
Figure 27: Radial linear stress.

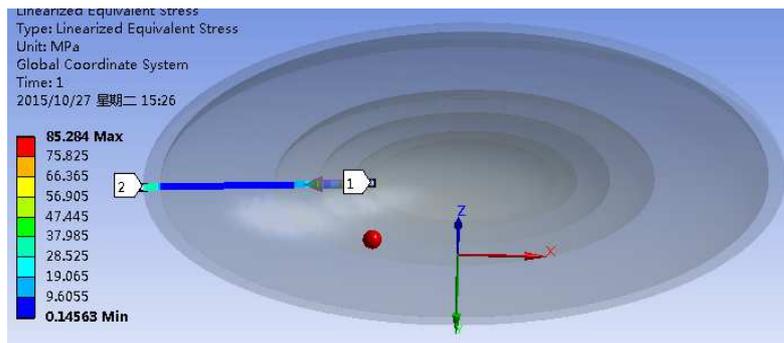Figure 28: Four kinds of radial linear stress.

Figure 29: Radial linear stress.

It can be seen in Fig. 28 that curve trend of the radial thickness stress, bending stress, peak and total stress value is very similar to the, linear maximum stress occurs at the 100 mm position. The total stress value at 260 mm is decreased to minimum of 12 mm, which means that the stress of explosive parts is relatively small.

5   Conclusion

Through the analysis of three different shapes of complex structure, it can be seen that under the same volume size, the cooling effect of the ellipsoid structure is better than that of the sphere structure. Equivalent stress appears more complex: The equivalent strain of the sphere is higher than that of the equal effect of same thickness of ellipsoid, but the equivalent strain of the sphere is lower than that of ellipsoid of constant value of the long diameter and short diameter ratio. The equivalent stress of the spherical part is lower than that of same thickness of ellipsoid and ellipsoid of constant value of the long diameter and short diameter ratio. The maximum stress and strain of the ellipsoid are located near the long diameter. From linear equivalent strain, the maximum stress strain is near the surface of beryllium parts and the stress of explosive parts is relatively low.

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