Modelling the Performance of Composite Material Barrel under Thermal-Mechanical Impact

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Abstract — In order to study the influence of the impact of powder gas with high temperature and high pressure on the composite material barrel, a three-dimensional thermal-mechanical analysis was conducted based on finite element analysis model. Regarding the fiber reinforced composite material barrel with metal liner as the research object, the finite element model of the barrel was established by using the nonlinear method. This paper firstly explored the influence of temperature-dependent material properties on the temperature field distribution of the barrel by the thermal load. Then, the stress field distribution was calculated by the non-coupled thermal-elastic theory. Finally, the stress field of the barrel was calculated by the coupled thermal-elastic theory. The effect of material nonlinearity on the temperature field distribution and the distribution law of stress under different load conditions was obtained. The results show that the thermal-mechanical impact loads can cause large transient stress, which clearly influences the strength of the metal liner properties. The paper provides a theoretical basis for the study of the damage of composite material barrel under thermal-mechanical loading.

Keywords - Composite material barrel; Non-linear thermal-elastic; Coupled thermal-mechanical; Finite element method

I. INTRODUCTION

Composite materials have been widely used in various engineering fields with their excellent properties. Fiber reinforced composite material has been successfully used in conventional weapons. There is also a certain degree of application in the artillery and automatic weapon components. However, these applications are confined to the secondary stress components. In terms of the main force for artillery components-barrel, abroad started early application of composite material and carried out a large number of experiments, made significant progress. Kollár [1] gave a solution of a dynamic response model of fiber-reinforced composite material cylinder withstanding variable mechanical and thermal loads which assumes the material is elastic. Brischetto et al [2] analyzed the coupling effects of composite laminated plates on thermal-mechanical aspect. Considering the hot and humid conditions, Jacquemin et al [3] established a semi-analytical model to calculate the stress field under the internal pressure loads. Mei et al [4] conducted theoretical modeling analysis on the carbon fiber composite materials under the thermal-mechanical cyclic loading, moreover, analytical solutions and experimental values were compared; Adopting the two methods of three-dimensional photoelastic experimental stress analysis and finite element calculation. At present China is still in the theoretical stage. Zhao et al [5] did some research on the interfacial shear stress of a three dimensional freezing slice of single-fiber pullout resin matrix composites under the combined effect of pullout loading and thermal residual stress. Based on microscopic damage mechanism, Wang et al [6] studied the fatigue life of metal matrix composites under the thermal-mechanical cyclic loading. Wu et al [7] conducted progressive failure analysis of composite thick-wall cylinder using continuum damage mechanics. Tian et al [8] did some work of experimental and numerical study on CFRP tube under axial crushing. Yan et al [9] studied the buckling of composite cylindrical shell under axial compression load. Few research is on thermal-mechanical shock load in all these studies. This paper focuses on the coupling mechanism and response of thermal-mechanical load for composite material cylinder with metal liner. The application of fiber reinforced composite material in the barrel is studied with the focus of the research group led by Professor Qian [10] of Nanjing University of Science and Technology. Mainly including: basic theory of composite materials barrel, stiffness-strength analysis of composite materials barrel, structure design and optimization of composite material barrel[11] and study on thermal property of composite material barrel[12]. Wang [13] analyzed the dynamic characteristics of composite materials barrel. Yang [14] studied the failure of carbon fiber reinforced composite material barrel. The theoretical system of composite materials has been basically formed. On the basis of the above research ,This paper focuses on temperature conduction and stress distribution of the composite material barrel under thermal-mechanical load, considering the nonlinearity of material and separate and coupling effect of thermal and pressure loads. All research is preparing for further study about the damage of composite material barrel under thermal-mechanical load.
II. THE FINITE ELEMENT EQUATION OF COMPOSITE MATERIAL BARREL

As coupling effect of pressure and thermal loads on the composite material barrel with metal inner, also due to the anisotropy of the composite and the loading conditions of strongly nonlinear, it is difficult to obtain the analytical solution. However, with the emergence of general nonlinear finite element analysis software, the problem can be solved by using the finite element method.

For the structure of composite materials barrel, since the composite material is anisotropic and there is off-axis material layer, the calculation result of simplified axis symmetric model or two-dimensional model exist some errors. The three-dimensional solid model is more accurate. Because of the complexity of temperature conditions, it is impossible to determine the temperature field accurately by the traditional analytical method. The finite element method is a convenient and effective tool to solve the above problems.

A. Heat Conduction Finite Element Equation

In the general three-dimensional problem, Field variable \( t \) of transient temperature field in the Cartesian coordinate system should meet the differential equation [15]:

\[
\rho \frac{\partial \phi}{\partial t} = \frac{k_x}{\partial x} \left( \frac{\partial \phi}{\partial x} \right) + \frac{k_y}{\partial y} \left( \frac{\partial \phi}{\partial y} \right) + \frac{k_z}{\partial z} \left( \frac{\partial \phi}{\partial z} \right) - \rho Q = 0
\]

(1)

The boundary conditions are:

\( \phi = \phi_0 \) (On the boundary of \( \Gamma_1 \)

(2)

\( k_x \frac{\partial \phi}{\partial x} n_x + k_y \frac{\partial \phi}{\partial y} n_y + k_z \frac{\partial \phi}{\partial z} n_z = q \) (On the boundary of \( \Gamma_2 \)

(3)

\( k_x \frac{\partial \phi}{\partial x} n_x + k_y \frac{\partial \phi}{\partial y} n_y + k_z \frac{\partial \phi}{\partial z} n_z = h(\phi_e - \phi) \) (On the boundary of \( \Gamma_3 \)

(4)

where, \( k_x, k_y, k_z \) are the thermal conductivity of the material along the three axis of the object respectively; \( \rho \) is density; \( c \) is specific heat capacity; \( t \) is time; \( \phi \) is the temperature; \( \phi, \phi_e, \phi_n \) are the direction cosine of the outside normal of the boundary; \( q, q_0, q_1 \) is the given temperature on the boundary; \( h \) is the heat transfer coefficient; For the boundary of \( \Gamma_2 \), \( h \) is also the heat transfer coefficient between the external environment and the adiabatic boundary layer.

For the formula (1) and boundary conditions (2) to (4), using the weighted residuals of Galerkin method, the equivalent variation principle is established, and the anisotropic three-dimensional steady-state heat conduction equation is derived.

\[
\Pi(\phi) = \frac{1}{2} \int_\Omega \left[ k_x \left( \frac{\partial \phi}{\partial x} \right)^2 + k_y \left( \frac{\partial \phi}{\partial y} \right)^2 + k_z \left( \frac{\partial \phi}{\partial z} \right)^2 \right] d\Omega - \int_\Gamma \rho(Qd\Gamma - \int_\Gamma h(\phi_e - \phi)d\Gamma)
\]

(5)

The finite element equations can be established by using the stationary condition \( \frac{\partial \Pi(\phi)}{\partial \phi} = 0 \) of the above-mentioned functional.

 transient heat conduction functional variation, as shown in the formula (6) the main difference with the steady heat conduction is not only a function of the spatial domain \( \Omega \), but also a function of the time domain \( t \).

\[
\int_\Omega \left[ \frac{\partial \phi}{\partial x} \frac{\partial \phi}{\partial x} + \frac{\partial \phi}{\partial y} \frac{\partial \phi}{\partial y} + \frac{\partial \phi}{\partial z} \frac{\partial \phi}{\partial z} \right] d\Omega - \int_\Gamma h(\phi_e - \phi)d\Gamma \]

(6)

B. The Nonlinear Thermal-elastic Finite Element Equations

Composite material barrel with metal inner, withstands transient thermal shock and its temperature changes fairly severely. The thermal parameters of metal and composite material will change as the temperature changes, which makes the thermal conductivity, specific heat capacity in finite element equation all relative with Temperature. This finite element model exhibits a temperature-related material nonlinearity.

Therefore, in the transient heat conduction, the temperature recursive format become

\[
\phi(\phi, \Delta t) = P(\phi, \Delta t) + C(\phi, \Delta t) \phi_{n+1} = P(\phi, \Delta t) + C(\phi, \Delta t) \phi_n
\]

(7)

where \( \phi^* = \phi - \phi_0 \) is the temperature change for a moment, \( \phi_0 \) is the reference initial temperature. The corresponding thermal strain caused by the change of temperature

\[
\varepsilon_0 = \alpha(\phi^*)(\phi - \phi_0)
\]

(8)

Meanwhile, the elastic matrix \( D \) in the stress-strain relationship \( \sigma = D(\varepsilon - \varepsilon_0) \) is also variable because the elastic modulus and Poisson’s ratio both change with temperature:

\[
E = E(\phi)
\]

(9)

Therefore, for composite anisotropic material
Where

\[
\begin{align*}
C_{11} &= (1 - \nu_2 \nu_3)E_1 \\
C_{22} &= (1 - \nu_1 \nu_3)E_2 \\
C_{33} &= (1 - \nu_1 \nu_2)E_3 \\
C_{12} &= (\nu_2 + \nu_1 \nu_3)E_1 \\
C_{13} &= (\nu_1 + \nu_2 \nu_3)E_1 \\
C_{23} &= (\nu_1 + \nu_2 \nu_3)E_2 \\
C_{44} &= C_{22} \\
C_{55} &= C_{33} \\
C_{66} &= G_{12} = G_6 \\
V &= 1 - \nu_1 \nu_2 - \nu_2 \nu_3 - \nu_1 \nu_3 - 2(\nu_1 \nu_2 \nu_3)
\end{align*}
\]

(10)

Thus, they are all expressed as the expressions of temperature \( \theta \). So, the finite element equation is

\[
K(\phi')u = P(\phi')
\]

(12)

From the Eq. (7~12), it can be seen that the finite element equation for thermal shock problem of composite material with metal liner is relative with the temperature. It is a nonlinear problem with temperature effect which is independent of the time.

III. **FINITE ELEMENT MODEL (FEM) OF COMPOSITE MATERIAL BARREL**

A. **Material Model**

The model is composed of a metal liner and four layers of carbon fiber-reinforced composite materials. The composite material barrel is a typical structure of revolving body. Its basic structure and the force as shown in Fig. (1), \( z \)-axis is the symmetry axis; \( r \)-axis is radial; \( \theta \)-axis is tangential ; \( 1 \)-axis is the direction of the composite fiber; \( 2 \)-axis perpendiculairs to the fiber direction; \( 3 \)-axis and \( r \)-axis are in the same direction; \( \alpha \) is the angle between \( 1 \)-axis and \( 2 \)-axis. Characteristics of fiber reinforced composite material show that, circumferential ply is beneficial to improve the strength of the laminate structure, axial ply is advantageous to improve the structural rigidity. In order to take the stiffness and strength of the barrel into account, the composite is made up of sixteen lays, which contain four layers of \( 0^\circ \)-lay, four layers of \( 45^\circ \)-lay, four layers of \( 90^\circ \)-lay and four layers of \( 0^\circ \)-lay from the inside to the outside. The thickness of the metal liner and the single layer of the composite material are 25 mm and 0.25 mm respectively. The axial length is 600 mm , and \( \epsilon = 79 \text{ mm} \).

The metal material is \( T300 \) steel and the composite material is \( T3000 \) which is a transversely isotropic material. The basic material parameters of metal and composite material at room temperature are shown in table 1.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>THE PHYSICAL PROPERTIES OF MATERIALS</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>( E_1 / \text{Mpa} )</td>
</tr>
<tr>
<td>( T300 )</td>
<td>181000</td>
</tr>
<tr>
<td>( N_{13} )</td>
<td>176900</td>
</tr>
</tbody>
</table>

B. **Boundary Conditions**

Considering stress analysis of composite material barrel with thermal effect and the nonlinearity of the material and the load condition, the inner wall of the barrel withstands the pressure and thermal loads produced by the propellant gas. The heat transfer type of the outer wall with atmosphere is free convection. In firing process, the heat transfer manner of the inner wall includes heat conduction, convection and radiation. Research has shown that the radiation is about one percent of the convection in exchanging energy, therefore, this paper mainly considers convection as the main heat transfer form.

When the artillery is firing, the interaction between propellant gas and the inner wall of barrel can be divided into three stages: interior ballistic period, aftereffect period and intermittent period. The heat transfer mode between the high temperature and high pressure gas with the inner wall of the barrel is forced-convection heat transfer during the interior ballistic period and aftereffect period, but the heat transfer coefficient is different. In the intermittent period, the pressure and temperature of the gas in the chamber are similar to that of the ambient medium. While the temperature of the inner wall is higher than that of the ambient, and the heat transfer mode between the inner wall with the environment is natural convection. During the whole firing process the outer wall of the barrel is heated by the natural convection heat transfer mode. Boundary conditions refer to the calculation results of the interior ballistic program in the literature [12]. As shown in Fig. (2) and Fig. (3), it does not consider the change of the load along the axial direction of the barrel.
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C. Calculation Process

1) In order to get the temperature distribution, the heat transfer analysis is carried out firstly. Considering the effect of thermal conductivity and specific heat capacity of nonlinear on heat conduction and temperature distribution, then steady and transient heat transfer analysis are carried out respectively. This paper mainly studies the nonlinear characteristic of material properties under thermal load and the effect of temperature-dependent material characteristics on temperature distribution. Physical properties of the metal and composite materials at room temperature are given in table 1 and temperature-dependent material parameters refer to literatures [16] and [17].

2) The temperature field is introduced into the model as loading condition, and the thermal-stress analysis is carried out. The structural elastic-plastic problem under the thermal load is mainly studied.

3) Transient and steady state fully coupled thermal-mechanical loads are calculated respectively. The interaction between thermal load and pressure load is analyzed. The main research contents are the real stress distribution of the barrel under the fully coupled thermal-mechanical load.

IV. HEAT TRANSFER ANALYSIS

In the material constitutive equations we need to consider the relationship between material parameters and temperature, which makes the relationship between stress, strain, temperature and heat conduction equation nonlinear. Firstly, the finite element model of the composite material barrel is established by the nonlinear finite element method, then the effect of the temperature-dependent thermal conductivity, specific heat capacity and other parameters of composite material barrel on the law of heat transfer and temperature distribution is analyzed.

A. Steady-state Heat Transfer Analysis

The effect of specific heat capacity and thermal conductivity on temperature distribution is studied at steady state by considering the temperature-dependent specific heat capacity and thermal conductivity of metal and composite material respectively. Research shows that the temperature-dependent specific heat capacity nearly does not affect the temperature conduction and distribution of the barrel, however, the effect of temperature-dependent thermal conductivity on temperature distribution is obviously. Calculation results are shown Fig. (4). In the following figures where A represents metal barrel, B represents composite material barrel without considering the nonlinearity of material parameters, C and D represent metal barrel and composite material barrel with considering the temperature-dependent thermal conductivity respectively.

As the thermal conductivity of the composite material is poorer than that of the metal, from Fig. (4) it can be seen that the temperature distribution is uneven and a turning point occurs at the interface between metal and composite material of composite material barrel. Considering the
temperature-dependent thermal conductivity of metal and composite material can reduce the temperature at the interface between metal and composite material, thereby reduce the temperature gathering at the interface, so it is beneficial to the diffusion of internal heat.

B. Transient-state Heat Transfer Analysis

The effect of temperature-dependent specific heat capacity and thermal conductivity on temperature distribution of composite material barrel is studied at transient state. Calculation results show that the temperature-dependent specific heat capacity nearly does not affect the conduction and distribution of temperature. Here we only show the effect of the thermal conductivity on the temperature distribution. The calculation results are shown in Fig. (5) to Fig. (7). When the transient-state heat transfer is carried out, the temperature of the region near the inner wall changes severely, but the temperature of the region far from the inner wall changes gently with obvious effect of thin layer. The temperature-dependent thermal conductivity of metal and composite material nearly does not affect the temperature distribution of the inner wall, however, the temperature of the region 2.5 mm from the inner wall and the interface change obviously, so it is beneficial to the temperature distribution.

According to the above calculation results it can be obtained that heat conduction and temperature distribution can be improved by changing the thermal conductivity of materials. So in terms of composite material, this paper considers adding heat conduction material in the matrix to improve the thermal conductivity of composite material, thereby reducing the temperature aggregation at the interface. Preparation and application of Al2O3 particle enhanced polyurethane modified epoxy composites are studied by Huang [18] who verify its feasibility.

When the artillery continuous shoots 8 times, the temperature distribution is shown in Fig. (8) where \( r_1 \) represents inner wall, \( r_2 \) represents the region 2.5 mm from the inner wall, \( r_3 \) represents the region 5 mm from the inner wall, \( r_4 \) represents interface and \( r_5 \) represents outer wall of the barrel. During the gun continuous firing, temperature of the inner wall of the barrel pulse changes and the temperature of the region near the inner wall changes severely. But the temperature of the region far from the
inner wall changes gently. With the number of shoots increasing, the temperature of the inner wall increases. Temperature difference exists between the internal and external wall of the barrel. Since the thermal conductivity of the composite material is poorer than that of metal, temperature difference slowly builds up in continuous shooting. The temperature of the composite layer is lower than that of the metal layer and the heat transfer in the composite material is slower than that in the metal, which is due to the poorer thermal conductivity of the composite material than metal. After the first shooting, the maximum temperature of each shooting increases, which adds to the barrel erosion and reduces the barrel life.

In the middle of the barrel stress distribution along radical direction is shown in Fig. (10), under the thermal load the metal layer is mainly affected by the axial tensile stress and the circumferential stress which at first is tensile stress then becomes compressive stress. This is because both ends of the barrel fixed and in the result of thermal expansion. In the metal layer, the axial stress and circumferential stress are uniformly distributed along the radical direction, which is in accordance with the stress analysis results of the pure metal thick-walled cylinder. As the thermal conductivity of the composite material is poorer than that of the metal, the temperature at the interface between metal and composite materials is accumulating, resulting in great thermal stress at the interface. Because of the difference of thermal expansion coefficient between metal and composite material, the stress changes severely at the interface. In the metal layer stress changes uniformly, but in the composite layer the stress distribution is not continuous because of the different direction of the fiber. There is an abrupt stress on the interface between the layers, but in each single layer the stress distribution is linear. This is consistent with the description of literature [19].

IV. THERMAL-STRESS ANALYSIS OF COMPOSITE MATERIAL BARREL

In this section, the thermal-stress analysis of composite material barrel is carried out. Temperature field inside the barrel has been obtained by the heat transfer analysis of the upper section, then the thermal-stress distribution of the barrel is obtained by structural analysis. The calculation process is shown in Fig. (9).

A. The Analysis of Thermal Stress at Steady State

In the following study, the effect of the temperature on the structure elastic-plastic is considered. The steady-state temperature field above is introduced into the model as loading condition, and the thermal-stress analysis is carried out. In the following figures MISES represents equivalent Vonmises stress; S11 represents radial stress; S22 represents circumferential stress; S33 represents axial stress.

B. The Analysis of Thermal Stress at Transient State

The transient-state temperature field above is introduced into the model as loading condition, then the thermal-stress analysis is carried out and the calculation results are shown in Fig. (11). In the transient heat conduction, the temperature of the inner wall becomes very high instantly and hardly has time to conduct, resulting in high temperature and large thermal stress near the region of the inner wall. The thermal load mainly products axial and circumferential stresses. As shown in Fig. (12), the farther away from the inner wall, the smaller the influence of the thermal load. The barrel still withstands the axial and circumferential stress, and the radial stress is nearly zero.
The temperature field of the artillery continuous shooting 8 times above is introduced into the model as loading condition, then the thermal-stress analysis is carried out and the calculation results are shown in Fig. (13). Equivalent Vonmises stress of the inner wall of the composite material barrel varies like pulsing, which is similar to the temperature variation during continuous firing. In the interior ballistic period, the thermal stress of the inner wall can reach 1200 Mpa. The radial stress is small, and the axial and circumferential stress is very large. All of the above is consistent with the literature [20].

From the above analysis of heat transfer and thermal stress it can be obtained that the temperature changes severely during the gun firing result in large thermal stress instantly. So the temperature has a great influence on the performance of the composite material barrel with metal liner. In particular, the effect of thermal load on the strength of the barrel can not be neglected.

VIV. FULLY COUPLED THERMAL-MECHANICAL ANALYSIS

The thermal load and the pressure load have a complex coupling relationship in the composite material barrel with metal liner. On the one hand, the temperature-dependent physical properties of the material are caused by the thermal load which generates thermal stress in the barrel at the same time. On the other hand, the structural deformation caused by the pressure load will change the distribution of the temperature field, while generating structural stress within the barrel.

In solving engineering problems of coupling field, there are two kinds of coupling analysis methods: sequentially coupled method and fully coupled method. If the sequentially coupled method is used, firstly the temperature field of the composite material barrel is obtained by heat transfer analysis, then taking temperature field as the boundary condition, the thermal-elastic analysis is carried out and the thermal-stress distribution is obtained. But this method does not consider the effect of the structural deformation on the temperature distribution. Actually, the structural deformation is a kind of functional transformation. The temperature field and stress field are coupled. Therefore, in order to obtain a more accurate stress distribution of the composite material barrel, the fully coupled method is used in this section. The calculation process is shown in Fig. (14).
A. The Analysis of Stress at Steady State

The pressure and thermal loads are used as the loading conditions, and the steady-state fully coupled analysis is carried out. The differences of calculation results between fully coupled load, pressure load and the thermal load are compared. Results are shown in Fig. (15), no matter which type of load, the stress mutates at the interface between the metal and the composite material; the stress change law is the same in the composite layer. The stress produced by the coupling load is greater than that of single pressure load and single thermal load; Stress distribution in the radial direction is substantially the same.

B. The Analysis of Stress at Transient State

The coupling effect is very strong in the interior ballistic period so this paper only studies the coupling effect of the internal ballistic period. It can be seen in Fig. (16) the stress produced by the pressure changes with the variation of the pressure curve. As the temperature increases, the thermal stress increases. Before 12ms the pressure is the main function, and the thermal stress is the main function. As shown in Fig. (17), the high temperature produced by the heat flow is only in the region near the inner wall, but does not have time to conduct, so in the area 5mm from the inner wall, the thermal stress is small.

IV. CONCLUSION

In this paper, the nonlinear finite element method is used to study the heat conduction, nonlinear thermal-elastic and coupled thermal-mechanical loads of composite material barrel. With the help of nonlinear finite element software ABAQUS analysis and calculation, the results show that when the gun fires, high temperature generates inside the barrel and it has significant effect of thin layer; due to the different material properties between the composite material and metal, the radial temperature distribution of the composite material barrel is not uniform; large temperature difference between the inner and outer wall of the barrel, which generates large thermal stress; considering the effect of dynamic term and coupling terms, it is more accurate to react the stress state of the barrel under the coupled thermal-mechanical load.
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