

Research Article

Analysis of the Temperature Field of a Gun Tube Based on Thermal-Solid Coupling

Wu Yong-hai

Faculty of Traffic Engineering, Huaiyin Institute of Technology, Huai'an 223003, China

Abstract: In this study, using a material model related to temperature, we calculate the transient temperature field of the gun tube subjected to the action of high-frequency cyclic dynamic thermal pulse and dynamic pressure pulse and analyze the couple effect of thermal pulse and pressure pulse and the distribution laws of the temperature field. Compared to the experimental data, the computational results are satisfactory on the whole. The results are important for the studies of gun tube temperature, life-span prediction as well as the way to improve the life-span of a gun tube. The model and the analysis method adopted here provide important references for gun tube design and improvement.

Keywords: FEA, gun tube, temperature field, thermal-solid

INTRODUCTION

When a machine gun is firing, the gun bore is subjected to the effect of high temperature, high pressure and high-speed powder gas. Firing continuously, periodic heating and cooling will induced violent temperature change to form unsteady thermal stress. The duration that the machine gun tube subjected to the thermal shock due to firing is pretty short and the amplitude is large. The temperature field and stress field of gun tube change drastically in short time, with the same time, heat deformation due to transient thermal shock will change with time, where mutation may occur and its speed is a function of time. The temperature field and stress field of gun tube couple and interact with each other. The firing rate of the machine gun is high and heating periodicity is short, so the coupling effect of temperature field and stress field is obvious. It's important to study the thermal effect of machine gun tube under the state of multi-physical fields coupling, which is significant for the gun tube design, life-span prediction as well as the way to improve life-span of gun tube. The thermal-solid couple model and the FEA model of machine gun tubes are established according to studying a certain 14.5mm caliber machine gun tube. Transient temperature field of the gun tube to the action of high-frequency cyclic dynamic thermal pulse and dynamic pressure pulse is calculated and the couple effect of thermal pulse and pressure pulse is analyzed and the distribution laws of the temperature field of the gun tube is analyzed, using a material model related to temperature. Compared with the experimental data, the results of calculation are satisfactory on the whole. The results are important for studies of gun tube temperature, life-span prediction as well as the way to improve life-span of gun tube. The model and analysis method

adopted in the study provides important references for gun tube design and improvement (Opjio and Jiapman, 1982). Kennedy *et al.* (1995) studies the simulated and experimental in-wall temperatures for 120 mm ammunition. (Lawton, 2003) analyze the thermal-chemical erosion in gun barrels. Lawton (2001) have a research of the influence of additives on the temperature, heat transfer, wear and fatigue life and self ignition characteristics of a 155 mm gun. Wu (2010) have a study on modern design theory of rapid-fire-weapon barrel. Kerwien and Rocha (1999) give a failure analysis of the m230 machine gun barrel-mif-a-001-1999-i. Conroy *et al.* (1995) have a research of the simulated and experimental in-wall temperatures for 120-mm ammunition.

In this study, using a material model related to temperature, we calculate the transient temperature field of the gun tube subjected to the action of high-frequency cyclic dynamic thermal pulse and dynamic pressure pulse and analyze the couple effect of thermal pulse and pressure pulse and the distribution laws of the temperature field. Compared to the experimental data, the computational results are satisfactory on the whole. The results are important for the studies of gun tube temperature, life-span prediction as well as the way to improve the life-span of a gun tube. The model and the analysis method adopted here provide important references for gun tube design and improvement.

Coupling temperature field mathematical models and fea model of gun tube: The physical model is simplified as two dimensional axis symmetric models according to the structure of the gun tube; the gun tube equation of coupling temperature field is obtained from thermodynamics and the law of heat transfer, as follows:

$$\rho c \frac{\partial T}{\partial t} - k \nabla^2 T + \beta T \frac{\partial e}{\partial t} = 0 \quad (1)$$

where,

$\beta T \frac{\partial e}{\partial t}$ = The coupling term

T = The gun tube temperature

t = The time coordinate

ρ = The material specific heat

c = The density

k = The thermal conductivity

∇^t = The Laplacian, cylinder coordinate

transforms is $\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2}$

e = The volumetric strain, $e = \frac{\partial u}{\partial r} + \frac{u}{r} + \frac{\partial w}{\partial z}$

u = The radial deformation

w = The axial deformation

r = The radius

β = The thermal stress coefficient, $\beta = E/(1 - 2\mu)$

E = The Elastic Modulus

μ = The Poisson ratio

The equations of coupling stress field of gun tube with axis symmetric transforms are as follows:

$$\begin{cases} (\lambda + 2G) \frac{\partial e}{\partial r} + G(\nabla^2 u - \frac{u}{r}) - \beta \frac{\partial T}{\partial r} = \rho \frac{\partial^2 u}{\partial t^2} \\ (\lambda + G) \frac{\partial e}{\partial z} + G\nabla^2 w - \beta \frac{\partial T}{\partial z} = \rho \frac{\partial^2 w}{\partial z^2} \end{cases}$$

where, $\beta \frac{\partial T}{\partial r}, \beta \frac{\partial T}{\partial z}$ are the coupling terms, λ, G are the Lamé constant, z is the axial coordinate.

The coupling multi-fields model is composed of Eq. (1) and Eq. (2).

Applying variation method to the above coupling model, the FEM matrix equations are:

$$\begin{bmatrix} M & [0] \\ [0] & [0] \end{bmatrix} \begin{Bmatrix} \dot{u} \\ \dot{T} \end{Bmatrix} + \begin{bmatrix} [0] & [0] \\ C^{uu} & C^t \end{bmatrix} \begin{Bmatrix} u \\ T \end{Bmatrix} + \begin{bmatrix} K & K^{ut} \\ [0] & K^t \end{bmatrix} \begin{Bmatrix} u \\ T \end{Bmatrix} = \begin{Bmatrix} F \\ Q_T \end{Bmatrix} \quad (3)$$

where,

M = The mass matrix

K = The stiffness matrix

K^{ut} = The thermo-elasticity stiffness matrix

K^t = The thermal conduction coefficient matrix

C^{uu} = The thermo-elasticity damp matrix

$C^{tu} = T_0 K^{ut} T$

C^t = The specific heat matrix

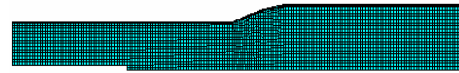
F = The load array

Q_T = The temperature load array

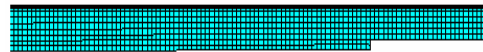
The gun tube is composed of the chrome layer and the steel body and it need to be taken as a double-tube processing when modeling. To improve computational efficiency, reduce unnecessary modeling structure and



(a) Gun tube



(b) The beginning of rifling region



(c) Muzzle region

Fig. 1: The FEA model of gun tube

save computing time, some local details on the gun tube orientation surface, holes, threads are simplified in this study. To analyze the effects of chromium plating on temperature field of the gun tube and a big temperature gradient existing on the thin wall of gun tube, the grid on the bore surface was properly clustered. The FEA model of the gun tube was generated with HYPERMESH software and a total of 21,167 nodes and 19,802 elements are obtained, as following. Figure 1 shows the FEA model of gun tube. (2)

Boundary condition: When firing continuously, the gun bore experiences periodical instantaneous change. A shooting circle is divided into 3 phases: interior ballistic period, the gas ejection period and the gas cooling period. Different expressions are adopted to calculate the temperature, pressure and powder gas forced convection coefficient of each phase as well as related parameters of gun bore airflow using interior ballistics model.

During firing, considerable temperature difference between high temperature and high pressure powder gas and bore surface will appear, surely induces heat exchange. The main modes of heat exchange are conduction convection and radiation. In the process of firing, the pressure and density of powder gas and absorption coefficient are quite high and most of radiation energy is absorbed before reaching the bore surface. Therefore, it can be assumed that only convection and conduction between the powder gas and gun bore exist, where radiation is compensated by correcting the forced convection coefficient of powder gas. The bore surface radius is r_1 :

$$\begin{cases} (\lambda + 2G) \frac{\partial u}{\partial r} + \lambda \frac{u}{r} - \beta \cdot (T(z, r_1) - T_0) - f(z, t) = 0 \\ k \frac{\partial u}{\partial r} + h_{inner} [T(z, r_1) - g(z, t)] = 0 \end{cases} \quad (4)$$

where,

$f(z, t)$ = The pressure function of gun bore

$g(z, t)$ = The gas flow temperature function of gun bore

Table 1: Basic physical parameters of gun tube

$T/^\circ\text{C}$	$k/\text{W/m/K}$	$c_p/\text{J/kg K}$	E/MPa
20	33.8	480.3	2.07e5
300	37.9	538.2	2.03e5
600	36.8	595.1	1.97e5
900	30.5	634.2	1.92e5
$t/^\circ\text{C}$	μ	α/K	$\rho/\text{kg/m}^3$
20	0.25	1.21e-5	7801
300	0.263	1.21e-5	7801
600	0.286	1.21e-5	7801
900	0.316	1.21e-5	7801

h_{inner} = The forced convection coefficient of gun bore

The outer surface of gun tube releases heat by the way of natural convection and radiation, its radius is r_2 :

$$\begin{cases} (\lambda + 2G) \frac{\partial u}{\partial r} + \lambda \frac{u}{r} - \beta \cdot (T(z, r_2) - T_0) = 0 \\ k \frac{\partial T}{\partial r} + h_{\text{outer}} (T(z, r_2) - T_0) + \varepsilon \sigma A [T^4(z, r) - T_0^4] = 0 \end{cases} \quad (5)$$

where,

- h_{outer} = The convection coefficient of gun tube outer surface
- T_0 = The environmental temperature
- ε = The radiance
- σ = The Steven-Boltzmann constant
- A = The radiation area

The initial condition is $u(r, 0) = 0$ and $T(r, 0) = 293$.

Material model and calculation methods: A certain gun tube, whose firing rate is 600 rounds/minute, is taken as research object. The material model is composed of the parameters of gun tube material which is needed for coupling model calculation. According to the above coupling model, the material model should include the following parameters: material density ρ , Elastic Modulus E , Poisson ratio μ , specific heat c_p , thermal conductivity k and thermal expansion coefficient α . considering temperature may affect the material physical performance and mechanics performance; the above parameters varying with temperature are obtained by referring to the engineering material manual. The values are given in the following Table 1.

FEM is adopted. Multi-fields coupling software ANSYS is taken as platform and APDL and FORTRAN code are used here, all of which are employed for the coupling model calculation. Two phase core flow model is adopted to calculate the interior ballistics parameters and the code, whose calculation results are used as input data of ANSYS, is inserted into ANSYS software. Axis symmetric model is used for the FEM model, which is simplified as 2 dimensional axis symmetric structures. It totally disperses 16826 nodes and 14642 elements.

The solution of coupling model belongs to transient dynamics non-linear problem and the material related to temperature is used and the nodes and elements are

numerous, so the calculation amount is huge and the requirement for calculation tools is high. HP working station is used to calculate the coupling model.

EXPERIMENTAL VERIFICATION

The following shooting criterions are used to verify the coupling model.

Shooting criterions is as follows. A cycle is composed of 100 rounds of projectiles and Group 1 (50 rounds) is for the three short firing continuously (7 rounds/sub-group) and a long firing continuously (29 rounds/sub-group) and the interval of short firing continuously is three seconds. Air cooling is 180s. The second group (50 rounds) is shooting in the same way. The water-cooling is used after three minutes of air-cooling until room temperature. Ambient temperature is 26°C and the firing rate is 608 rounds/minute. In order to make the experiment result have a certain degree of representative, 8 spots in the outer surface of the gun tube are selected along the axial direction. The experimental and computational values on measurement spots are given in Table 1. As the temperature measurement values are very sensitive to the time and considering the time error of value measuring in the experiment, a certain time delay of calculated value is done by the number order. Compared with the experimental data in the following

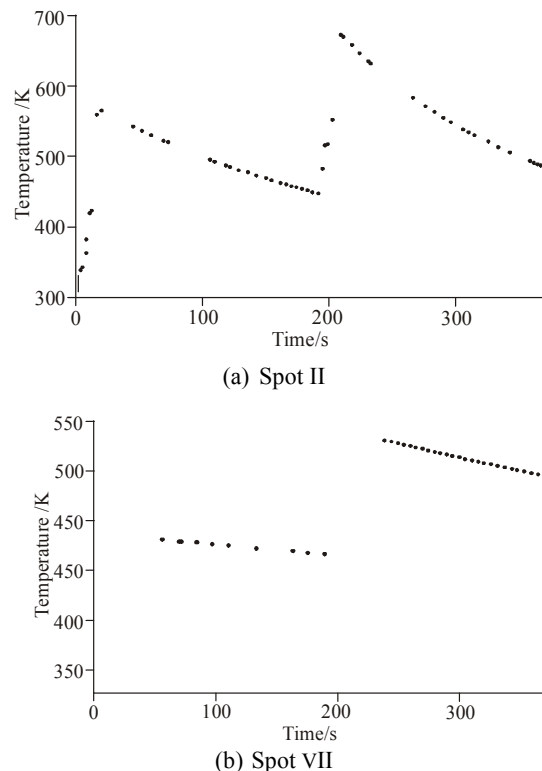


Fig. 2: The temperature history of measurement spots (calculated values)

Table 2: Model validation data

	Spot I	Spot II	Spot VII
Coordinates (mm)	1314	1274	412
The first group of experimental data (°C)	276	284	201
Calculated values(°C)	276.7	289.17	203.05
The second group of experimental data (°C)	408.6	392	302.7
Calculated values (°C)	385.66	391.68	310.12

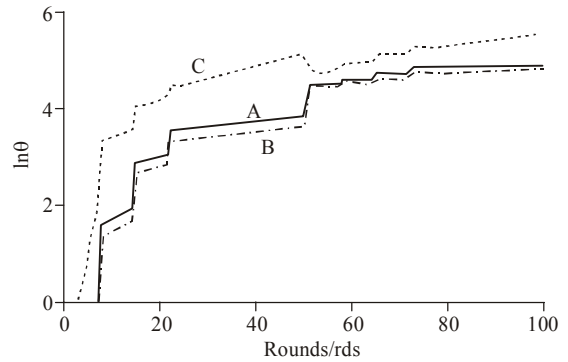
table, the computational results of coupling model are satisfactory on the whole. The maximum value of the error appears in the measurement spot VIII of the 2nd group and the maximum percentage of the error is 13.7%.

Figure 2 shows the temperature history (calculated values) for Spot II and VIII in Table 2. Spot II is located at muzzle region and the wall thickness is about 7 mm. Spot VIII is located on the region of the maximum chamber pressure and the wall thickness is about 21 mm. In the stage of firing continuously in the first group and second group, the curve of Fig. 2a have 3 times remarkable fluctuations and the fluctuations are respectively corresponding to the three sub-groups of short firing continuously (7 rounds/minute, sub-group interval time is 3s). The curve in Fig. 2b is very smooth, because the wall where the Spot 2 is located is thin and the temperature of the inner wall spreads to the outer wall rapidly; while the wall where the Spot 8 locates is thick, which is about 3 times of Spot II. The temperature response bands of the outer wall have a certain delay. Therefore, it does not reflect the shooting state of the inner wall. The same state appears in the three minutes' air-cooling stage. In Fig. 2a, it is clear that the temperature experienced a significant decline after a short-term rise. The temperature of Fig. 2b has a longer rise time and a more moderate decrease.

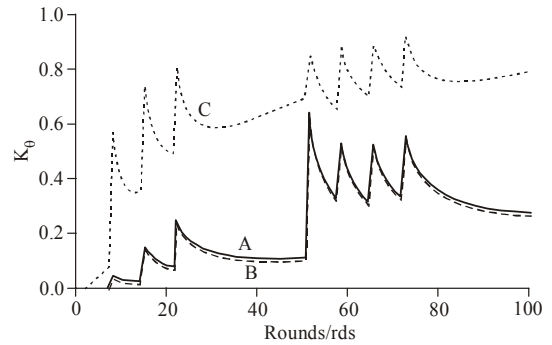
TEMPERATURE FIELD CALCULATION RESULTS AND ANALYSIS

To fully reflect the thermal state of the gun tube, three-section temperature fields on the gun tube are selected to be analyzed. Section A is located at the start rifling region, which is 108mm from the gun breech. Section B is located at the largest chamber pressure region, which is 223.4 mm from the gun breech. Section C is located at muzzle region, which is 1314 mm from the gun breech.

When the machine-gun shoots continuously, gun tube temperature field is always in a state of non-equilibrium and it is a cyclical problem of unsteady heat conduction. According to heat transfer theory, no steady-state thermal conductivity is divided into 2 phases: the initial stage and the formal situation. When the gun tube comes into the formal state of thermal conductivity after the initial stage, its value is only related to geometric position and boundary conditions and has nothing to do with time t. Taking advantage of this characteristic, gun tube temperature field can be



(a) Formal status of phase diagram



(b) Coefficient of variation curve of the relative temperature rise

Fig. 3: Temperature field state of gun tube

forecast and it is of great significance for the control of the gun tube temperature field. Stage of the formal status has 2 features. Firstly, the excess temperature of any point on objects is a constant to time change rate. That is, the rate of heating (or cooling rate) is a constant. Figure 3a is the formal status of phase diagram of gun tube. If the situation of the gun tube comes into the formal stage, the curve slopes on the three sections should be the same. As seen from the graph, after the 2 groups of shooting experience, the gun tube did not enter the formal status of stage. Secondly, the relative temperature rise coefficient of any spot on the object is a constant. Figure 3 is the relative temperature rise coefficient curve. In the figure, the relationship between temperature rise of the outer and the inner wall caused by single shot is: $K_{\theta} \frac{\theta_{outer}}{\theta_{inner}} = \frac{T(r_2,t)-T_a}{T(r_1,t)-T_a}$. In the formula, K_{θ} is the coefficient of the relative temperature rise; θ_{out} is the excess temperature of the outer wall; θ_{inner} is the excess temperature of the inner bore. If the distribution of gun tube temperature appears in the formal stage, the coefficient of the relative temperature rise of the outer wall and inner bore should be a constant. Figure 3b is the corresponding norms of the gun tube in the firing temperature rise relative coefficient map. It is clear that the relative temperature rise coefficients of the gun tube

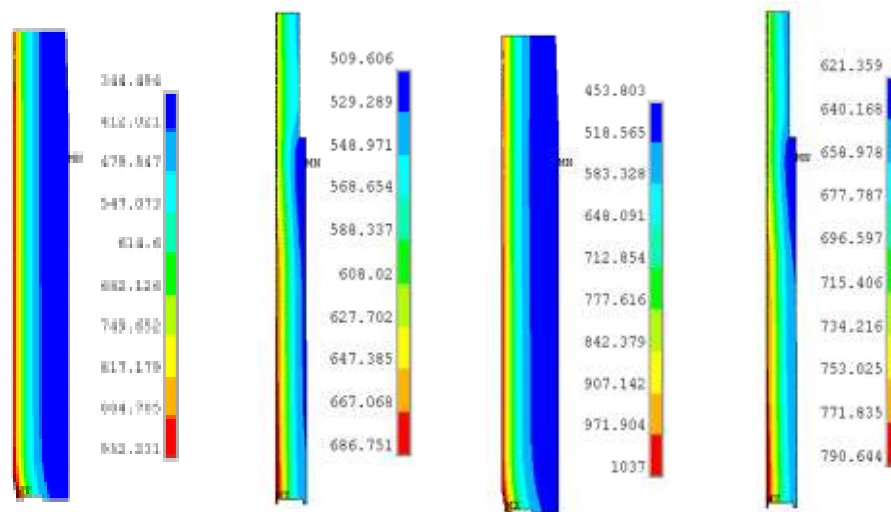


Fig. 4: Temperature field distribution of the gun tube. (a) The maximum chamber pressure region after 50 rounds shoot, (b) The muzzle region after 50 rounds shoot, (c) The maximum chamber pressure region after 100 rounds shoot, (d) The muzzle region after 100 rounds shoot

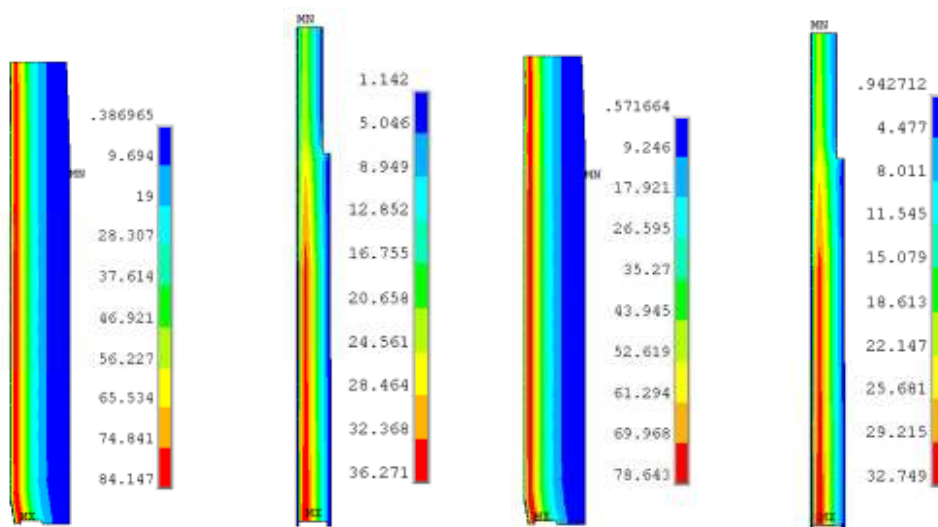


Fig. 5: Temperature gradient distribution of the gun tube. (a) The maximum chamber pressure region after 50 rounds shoot, (b) The muzzle region after 50 rounds shoot, (c) The maximum chamber pressure region after 100 rounds shoot, (d) The muzzle region after 100 rounds shoot

are all not constants. For machine gun tube, due to the high firing rate, the velocity limitation of material heat transfer and the limitation of the natural dissipation of air-cooling, with the increase of the projectile number, heat gathers in the gun tube wall and causes the situation that the gun tube temperature has already reached the limit permitted temperature before the gun tube enters the formal stage.

Figure 4 and 5 are the distributions of thermal state of the gun tube. As can be seen from the figures, after the end of the group 1 (50 rounds) shoot, in the initial part of rifle, the region near the wall has higher temperature, the farther away from the wall, the lower

the temperature and outer temperature. As the wall is thick, the temperature difference between the inner and outer wall is big. The total difference is 607.7 K. The distribution of temperature gradient in the tube is big and the distribution of heat flow is uneven. The largest heat flow appears in the thin layer near the bore; while in the muzzle region, for the gun tube wall is thin, the temperature difference between the inner and outer wall is only 177.1 K. The temperature gradient in the tube is small, but the overall temperature is high and the heat flow is big. After the launch of group 2, the basal temperature of the tube wall rises. In the initial region of the rifle, the temperature difference between the inner

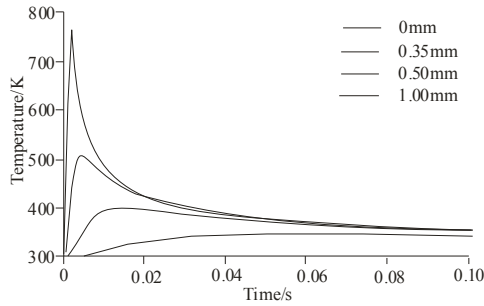
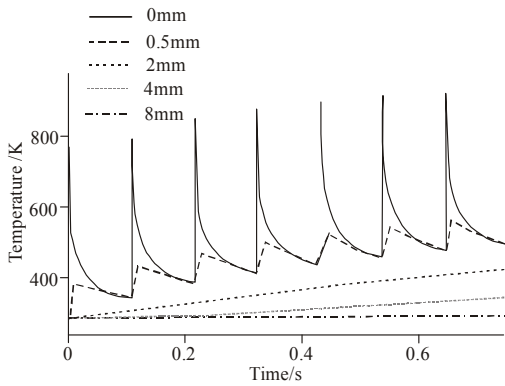
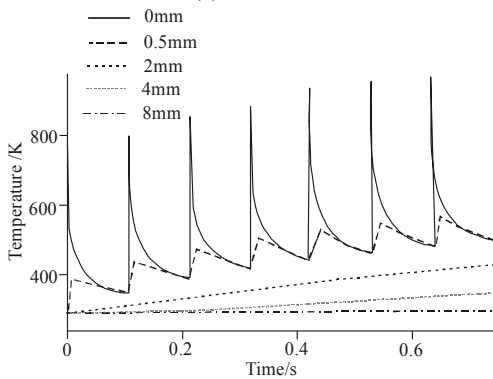


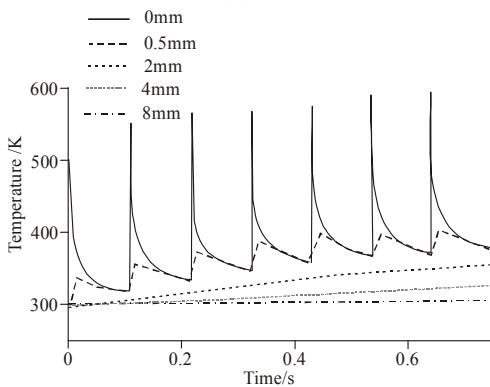
Fig. 6: Temperature curve of single shoot (section A)



(a) Section A



(b) Section B



(c) Section C

Fig. 7: Temperature curve in different section when firing continuously

and outer wall drops. The temperature of inner wall rises 84.8K and the outer wall rises 165.1 K. The temperature difference between the inner and outer wall is 584.8 K. The temperature gradient declines and the heat flow increases.

Including the interior-ballistics period and the air-cooling period, the gun tube has only 0.0108s to obtain the heat during a single shoot from the interior-ballistics calculation. When shooting in single, the bore point temperature in section A rises from ambient temperature to 992.8 K quickly in 0.00272s and then decrease and declines to 387.3 K after the end of the air cooling period. It is showed that the temperature response curve of gun tube bore surface have pulse-like shape in Fig. 6 and 7 under the condition of the transient strong thermal shock of powder gases. The bore surface temperature appears in the law of sharp increasing and then declining rapidly and the amplitude of temperature response weakens greatly outward radially. The peak temperature of the chromium layer surface is 992.8 K. The peak temperature is 617.6 K in the interface between chrome layer and steel layer. The peak temperature of the point which is 1mm outward away from the bore along the radius is only 368.3 K. Radial distance of 4mm away from the bore, the temperature fluctuations can not be seen basically. The temperature response shows a slow upward trend.

When continuously firing, the temperature response of the gun tube bore shows a rising trend in pulse. However, the amplitude of the temperature response increases gradually slowly with the increase in the number of shoot. In the initial part of the rifle, the peak bore temperature increases 42.7 K when the second bullet is shot. When the 7th shot is finished, the peak temperature increases only 13.9 K from the end of the 6th shot. The temperature laws of the gun tube bore at different axial sections are similar; however, the peak temperature values have larger differences, as shown in Fig. 7b and c. When shooting in single, the peak temperature value in section B is 798.9K and the peak temperature value in section C is 540.1 K. The difference between section B and section C is 258.8 K.

Figure 8 indicates that the thickness invaded by heat of cross-section on maximum chamber pressure changes over time. As time increases, the heat flow expands along the radial continuously and the corresponding temperature differences gradually decrease. At the end of the interior ballistics period, the thickness invaded by the heat is 0.98mm and the maximum temperature difference is 678.2 K. After the intermediate period, the thickness invaded by the heat is 1.976 mm and the maximum temperature difference is 268.1 K. After the firing interval period, the thickness invaded by the heat is 4.04 mm and the maximum temperature difference is 86.9 K. At the same time, Fig. 8 shows the temperature distribution rapidly declines radially in the launch period. When the time comes to 0.00272s, the

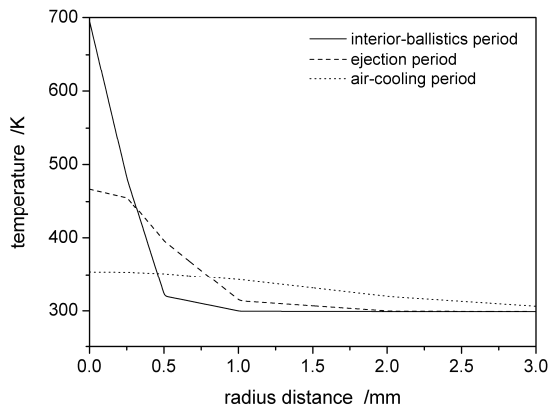
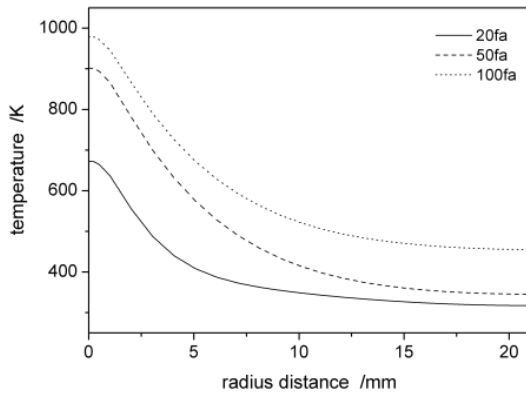
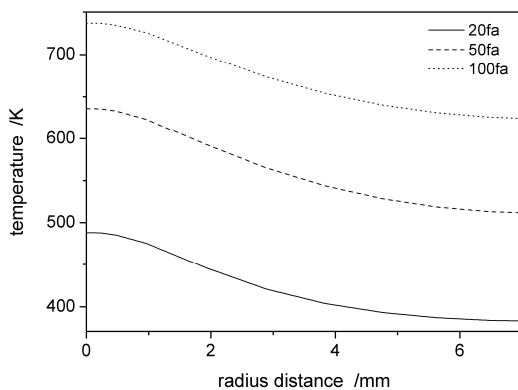


Fig. 8: Teat effect thicknesses in section A when single shoot



(a) Section B



(b) Section C

Fig. 9: Teat effect thickness when firing continuously

peak temperature gradient appears at about 0.5 mm radically away from the bore surface and the value is $3.29E5K/m$. When the time comes to 0.1s, the peak temperature gradient migrates about 1.01 mm outward radically away from the gun tube bore surface and the value rapidly declines to $3.58E3K/m$. Figure 8 indicates the region where temperature changes drastically

focuses on the thin layer of the gun tube bore. Due to the short of the heat transfer time, only the thin metal layer close to the gun tube bore has a chance to absorb the energy of powder gases and then the heat spreads both along the radial and axial directions in the gun wall.

Figure 9a shows the temperature distribution of the maximum chamber pressure cross-section. With the number of shoot increases, the temperatures of cross-section points rise, but are not synchro. Comparing the temperatures after 50 shots with the temperature after 20 shots, the bore surface temperature rises 229.4 K, while the outer surface temperature rises only 28 K. At the end of 100 shots, compared to the end of 50 shots, the bore surface temperature rises only 77.3 K, while the outer surface temperature rises 109.6 K. This is because the time of air-cooling period between 2 shoot groups is 180s and the heat in the gun wall has enough time to spread. At the end of the air-cooling period, the bore surface temperature drops 486.3 K, while the outer surface temperature rises 68.1 K. excluding the effect of air-cooling period, in fact, the bore surface temperature of section A rises 563.6 K, while the outer node temperature rises only 41.5 K.

Figure 9b shows the temperature distribution of the C-section (in muzzle region) when continuously firing. With the number of shoot increasing, the temperature value at each point appears in the law of rising basically synchronously. At the end of 50 shots, the bore surface temperature rises 147.7 K and the outer surface temperature rises 128.1 K. At the end of 100 shots, the bore surface temperature rises 101.1K and the outer surface temperature rises 112.6 K. This law is obviously different from Fig. 9a and this is because the thickness of section C is only 1/3 of section B. At the same time, the heat flow spreads to the outer surface of the gun tube and the temperature of outer surface point simultaneously increases.

CONCLUSION

The following conclusions can be obtained from the above calculation and analysis:

- When the machine gun shoots continuously, as the firing rate, the gun tube material, wall thickness, shooting criterions and other factors, before the inner wall temperature reaches the limit one, gun tube temperature field is always in the initial stage of no steady thermal conductivity and cannot enter the phase of the formal situation. Therefore, the technology method which using the outer wall temperature of gun tube to predict inner wall temperature is not feasible
- The bore surface temperature response caused by the thermal load was shaped pulse. When shooting continuously, the pulse peak rises rapidly firstly and then slows down gradually. The pulse amplitude

decreases, however, residue temperature in the inner wall surface increases significantly

- Thermal load caused the thin-layer effect significantly. Outward radially, the amplitude of the temperature response weakens greatly and the exquisite change region focuses on the thin inner wall of bore. The temperature distribution within the gun tube is associated with gun tube wall thickness
- When shooting continuously, within the initial rifle regions with thick wall, the heat is accumulated in the wall of the gun tube and can't expand outward in very short time. As a result, the temperature of inner wall is high but of outer wall is low. During the period of the gun tube cooling, the heat expands rapidly and the temperature of inner wall decreases significantly. In the muzzle region where the thickness is thin, the temperatures of both inner and outer wall rise or decrease synchronously

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