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Study on Transient Temperature and Stress of Gun Barrel Subjected to Periodic Pressure and Thermal Pulse

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Abstract

A large-caliber machine-gun is more firing rate, less weight and less barrel wall thickness. When firing continuously, the transient temperature and thermal-solid coupling stress have great influence on barrel strength as well as its operational safety. A FEA barrel model of thermal-solid coupling is established. The transient temperature and coupling stress of a large-caliber barrel under the effect of both periodic pressure and heat shock are presented. The FEA model is verified and the computational results are summarized below. (1) The bore surface temperature is shaped pulse. When shooting continuously, the pulse peak rises rapidly firstly and then slows down gradually. The exquisite change region focuses on the thin inner wall of bore. The estimation and improvement of large-caliber gun barrel life must consider the transient temperature data. (2) The coupling action of thermal shock and pressure pulse has great effect on the transient stresses of gun barrel. The radial stress is mostly induced by chamber-pressure; the axial stress is primarily induced by thermal load; the hoop stress is the coupling action of the chamber-pressure load and thermal load. The strength design of large-caliber gun barrel should consider the coupling action of thermal shock and pressure pulse.

Keywords

Temperature field, stress field, thermal-solid coupling, large-caliber machine-gun, gun barrel.

1. Introduction

When machine gun firing continuously, the barrel is under the effect of powder gas of high speed, temperature and pressure, and the acute variation of temperature and stress in barrel is caused by the periodic loads of temperature and pressure. The phenomenon is important for operational safety of barrel. The temperature and thermal stress of gun barrel have been studied by many researchers[1-5]. Boisson et al[6] built one and two dimensional thermal models on barrel heated and cooled. Lee et al[7] studied the heat stress of a multi-layer barrel. Wu et al[8] analyzed the temperature field of a 12.7mm machine gun. While there is a little study about thermal-solid coupling problem of machine-gun barrel. Wu et al[9] established a thermoelasticity barrel model and calculated the stress as well as temperature of 12.7mm machine-gun barrel. A certain large-caliber single-barrel antiaircraft machine-gun is more firing rate and less barrel wall thickness. The coupling action of thermal shock and pressure pulse has great effect on service safety and life of gun barrel due to the continuous firing. However so far, there is less study on thermal-solid coupling problem of large-caliber gun barrel. The purpose of this paper is to investigate the transient temperature and stress of a certain large-caliber gun barrel under the effect of both dynamic thermal and pressure loads varying periodically in high-frequency, and to offer advices on strength and life design of large-caliber gun barrel.

2. Thermal-solid Coupling Model of Gun Barrel

2.1 Two-dimensional Axisymmetric Thermal-solid Coupling Model

Based on barrel structure, the physical model can be idealized as a 2D axisymmetric model. The equation of barrel coupling with temperature is educed from thermodynamics, as below:

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

where ρ is density; c is specific heat of material; T is temperature of barrel; k is thermal conductivity; $\nabla^2=\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{\partial^2}{\partial z^2}$ is Laplacian; $e=\frac{\partial u}{\partial r}+\frac{u}{r}+\frac{\partial w}{\partial z}$ is volumetric strain; u and w are deformations respectively along radial and axial directions; t and z are time and axial coordinate respectively; r is radius; $\beta=E/(1-2\mu)$ is coefficient of thermal stress; μ is Poisson ratio; E is elastic modulus.

The equations of barrel coupling with stress using axisymmetric transformation are as follows[7]:

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

where λ and G are Lame constants. The coupling model is composed of equation (1) and (2).

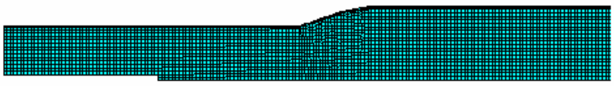
Based on the coupling model, the FEM equations listed below are obtained with variation method.

$$\begin{bmatrix}M & [0]\\ [0] & [0]\end{bmatrix}\begin{Bmatrix}\ddot{u}\\ \ddot{T}\end{Bmatrix}+\begin{bmatrix}[0] & [0]\\ C^{tu} & C^{t}\end{bmatrix}\begin{bmatrix}\dot{u}\\ \dot{T}\end{bmatrix}+\begin{bmatrix}K & K^{ut}\\ [0] & K^{t}\end{bmatrix}\begin{Bmatrix}u\\ T\end{Bmatrix}=\begin{Bmatrix}F\\ Q_T\end{Bmatrix} \tag{3}$$

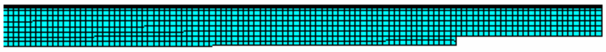
where M and K are matrices of mass and stiffness respectively; K^{ut} and K^t are matrices of thermoelasticity stiffness and thermal conduction coefficient respectively; $C^{tu}=T_0K^{utT}$ and C^t are matrices of thermoelasticity damp and specific heat respectively; F and Q_T are arrays of load and temperature load respectively.

The barrel comprises steel body and chrome layer, which should be modeled in the manner of double-tube. To reduce modeling structure and save computing time, some unnecessary structural details are idealized. To analyze the effects of chromium plating on temperature of barrel, and due to the high temperature gradient existing on thin wall of barrel, the grid on bore surface is clustered appropriately. The FEA model is got using Hypermesh, and a total of near twenty-one thousand nodes and twenty thousand elements are obtained (demonstrated in Fig.1).

(a) Gun barrel



(b) Beginning of rifling



(c) Around muzzle

Fig.1 Barrel FEA model

2.2 Boundary Conditions

A shooting circle is composed of interior-ballistic phase, gas-ejection phase and gas cooling phase. Different formulas are employed here to compute the parameters of bore airflow at different phases based on interior ballistics[9].

(1) *Boundary condition on bore surface*

In the course of firing, remarkable difference of temperature between powder gas and bore surface comes into being, and arouses heat exchange. The heat exchange is carried out through convection, conduction and radiation. During firing, radiation energy of powder gas is absorbed mostly before getting to bore surface. Thus only convection and conduction between bore and powder gas appear, and radiation is considered by modifying the coefficient of forced convection[10]. In addition, the heat acted on the bore surface can be ignored in the process of projectile moving in the bore, because the projectile passes through the bore very quickly; while the heat acted on the bore surface can't be ignored when the projectile crushes into the rifling, because the crushing velocity of projectile is slow relatively. Thus, the boundary condition on bore surface can be written as equation (4), where the radius r is r_1.

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

where $f(z, t)$ is pressure function; $g(z, t)$ is temperature function of gas flow; h_{inner} is coefficient of forced convection.

(2) *Boundary condition on outer surface*

The outer surface of barrel liberates heat through natural radiation and convection, and therefore the boundary condition at outer surface can be described as equation (5), where the radius r is r_2。

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

where h_{outer} is convection coefficient of outer surface; ε is radiance; T_0 is environmental temperature; A is area of radiation; σ is Steven-Boltzmann constant.

(3) *Methods for computing important parameters in boundary conditions*

As discussed above, the boundary conditions acted on barrel is affected by the temperature, pressure, coefficient of forced convection of powder gas, convection coefficient of outer flow, environmental temperature and radiation ratio. Specially, the temperature and coefficient of forced convection of powder gas is very important for computing both the temperature and stress fields.

(a) *Variation of temperature of powder gas* $T_g(t)$

Temperature of powder gas at interior ballistic period:

$$T_g(t)=\left[1-{(k-1)\phi q v(t)^2}\big/{(2f\omega\psi)}\right]T_1 \tag{6}$$

where $v(t)$ is projectile velocity; q is projectile mass; ω is load of powder; k is adiabatic coefficient; φ is virtual coefficient; ψ is percentage of powder burned.

Temperature of powder gas at gas ejection period:

$$T_g(t)=T_{bw}*e^{-At^B} \tag{7}$$

where T_{bw} is explosion temperature of powder; A and B are fitting exponents to be computed: $B=\ln\left[\frac{\ln(T_k/T_{bw})}{\ln(T_a/T_{bw})}\right]/\ln\left[\frac{t_{ndd}}{t_{ndd}+t_{hxq}}\right]$, $A=-\ln(T_k/T_{bw})/t_{ndd}^B$; T_k is average temperature of powder gas in bore at the end of interior ballistic period; T_a is average temperature of powder gas in bore at the end of gas ejection period; t_{ndd} is duration of interior ballistic period; t_{hxq} is duration of gas ejection period.

(b) *Coefficient of forced convection of powder gas*

Coefficient of forced convection of powder gas at interior ballistic period is obtained using similarity theory:

$$h(x,t)=0.023\frac{K_g(t)}{d}\left[\frac{V_g(t)\rho_g(t)d}{\mu_g(t)}\right]^{0.8}\cdot\left[\frac{C_{pg}(t)\mu_g(t)}{K_g(t)}\right]^{0.4}K_c \tag{8}$$

Where $V_g(t)$, $K_g(t)$, $\rho_g(t)$, $\mu_g(t)$, $C_{pg}(t)$ are flow velocity, coefficient of thermal conductivity, density, viscosity and specific heat of powder gas; K_c is correction coefficient of radiation.

Forced convection coefficient of powder gas at gas ejection period is computed with:

$$h(x,t) = 0.02\left[\frac{V^* d\rho_g(t)}{2\mu_g(t)}\right]\rho_g(t)\frac{V^*}{2}c_{Pg}(t) \tag{9}$$

where $V^* = \sqrt{2kRT_{hx}/(k+1)}$ is average critical velocity of powder gas; R is gas constant; T_{hx} is average temperature of powder gas in barrel at gas ejection phase.

At gas cooling period, blazing gun barrel releases hot by means of natural convection. When the gas flow is laminar, the convection coefficient is:

$$h(x,t) = 1.32\left(\frac{T_w(x,t)-T_a}{d}\right)^{0.25} \tag{10}$$

while the gas flow is turbulent, the convection coefficient is:

$$h(x,t) = 1.2(T_w(x,t)-T_a)^{1/3} \tag{11}$$

Where T_a is ambient temperature.

(4) *Initial condition*

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

2.3 Material Model and Numerical Methods

The large calibre barrel firing at 608 rounds per minute is researched here. Based on the coupling model discussed above, the material model is composed of density ρ, Poisson ratio μ, elastic modulus E, thermal conductivity k, specific heat c, coefficient of thermal expansion α. The effect of temperature on physical and mechanics performance of material is considered here, which is listed in Table 1.

Table 1 Material parameters of barrel

t /°C	K /W·m^{-1}·K^{-1}	C_P /J·kg^{-1}·K^{-1}	E /MPa	M ——	α / K^{-1}	ρ /kg·m^{-3}
20	33.8	480.3	2.07×10^5	0.25	1.21×10^{-5}	7801
300	37.9	538.2	2.03×10^5	0.263	1.21×10^{-5}	7801
600	36.8	595.1	1.97×10^5	0.286	1.21×10^{-5}	7801
900	30.5	634.2	1.92×10^5	0.316	1.21×10^{-5}	7801

FEM is employed here and ANSYS is adopted as the solving frame of coupling model. In addition, FORTRAN codes as well as APDL codes are also applied. The flow model of two phase is used to describe the interior ballistics, and its codes are combined with ANSYS to provide input data for ANSYS. The above coupling model is a non-linear problem, and the solution is transient and dynamic. Meanwhile, the material model correlated to temperature is adopted here.

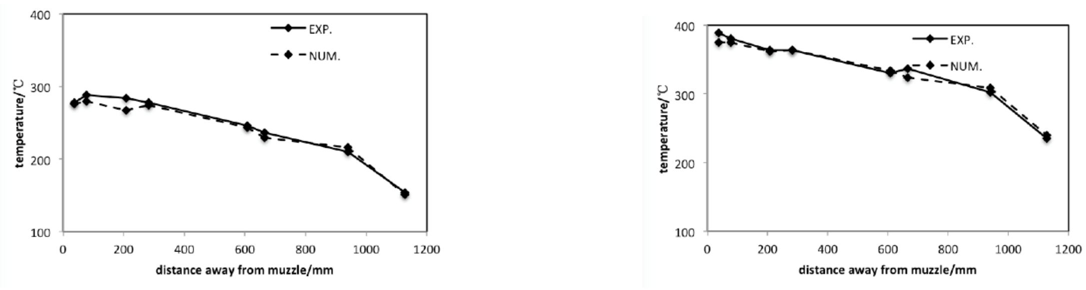
3. Experimental Verification

The following shooting criterion is used to verify the thermal-solid coupling model, and the rate of firing continuously is 608 rounds per minute. One firing cycle includes 100 rounds, which is divided into group 1 (the first 50 rounds) and group 2 (the last 50 rounds). Group 1 and Group 2 are performed in the same way. One group is composed of one long bunch (29 rounds per bunch) and three short bunches (7 rounds per bunch) of continuously firing. The interval between short bunches is 3 seconds and the period of air cooling is 180 seconds. Shortly after air cooling, water cooling is carried out until the ambient temperature 26°C.

For ensuring the typical significance of experimental result, 8 spots on outer surface of barrel are selected axially to measure the physical parameters. The computational results of temperature based on the above thermal-solid coupling model are compared with experimental values in Table 2 and Fig.2, and it can be seen that they are coincident as a whole. The maximum diversity emerges at spot III in group 1, and the corresponding relative difference is 4.69%.

Table 2 Model validation data

Spot	spot I	spot II	spot III	spot IV	spot V	spot VI	spot VII	spot VIII
Distance away from muzzle (mm)	38	78	208	282	608	665	940	1128
Group 1 Experimental data (°C)	278	288	284.33	277.33	246	236	209.67	154
Calculated values(°C)	276.29	279.91	267.03	274.58	243.57	229.47	216.39	150.88
Group 2 Experimental data (°C)	388.67	380.33	363.67	364	330.67	337	302.67	235.33
Calculated values (°C)	374.49	374.48	361.92	363.35	334.14	324.07	308.99	239.81



(a) Group 1 (b) Group 2

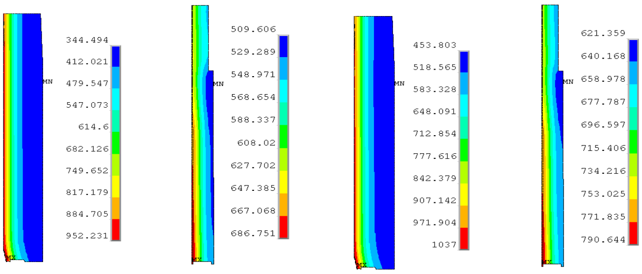
Fig.2 Model validation data

4. Numerical Results of Temperature and Stress

4.1 The Transient Temperature of Gun Barrel

For well describing the thermal and mechanical state, 3 sections on barrel are selected axially to analyze the temperature and stress. Section A is 108.0 mm away from barrel breech and near the beginning region of rifling; Section B is 223.4 mm away from barrel breech and at the location of the highest bore pressure emerging. Section C is 1314.0 mm away from barrel breech and near muzzle. The firing cycle is as same as that adopted by experimental verification.

The temperature field on barrel is demonstrated in Fig.3. After firing of group 1, at the start region of rifling, the temperature acutely declines more than 600K from inner to outer surface of wall. The gradient of temperature in barrel is steep, and the field of heat flow is irregular. The largest heat flux comes into being in a thin region near bore. Near muzzle, for the wall of barrel is thin, the temperature declines only less than 180K radially outwards from inner to outer surface. The gradient of temperature in barrel near muzzle is weak, though the temperature there is high in general and the heat flux is notable. After firing of group 2, the temperature of barrel increases as a whole. At the beginning part of rifling, the temperature declines about 580K axially from inner to outer surface, which is less than that emerging after firing of group 1. Meanwhile, the gradient of temperature decreases, while the heat flux increases. The peak location of heat flux moves axially outwards. Near muzzle, the temperature of barrel rises in the mass, while the gradient decrease slightly.



(a) (b) (c) (d)

Fig.3 Temperature of barrel

(a) Around highest bore pressure after group 1; (b) Around muzzle after group 1;

(c) Around highest bore pressure after group 2; (d) Around muzzle after group 2.

Temperature curve of single shoot at section A is shown in Fig.4. 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 992.8K quickly in 0.00272s, and then decrease, and declines to 387.3K after the end of the air cooling period. It is shown that the temperature response curve of barrel bore surface have pulse-like shape under the condition of the transient strong thermal and pressure actions of powder gases. The bore surface temperature appears 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 992.8K. The peak temperature is 617.6K in the interface between chrome layer and steel layer. The peak temperature of the point which is 1mm outward away from the bore alone the radius is only 368.3K. At the point of radial distance of 4mm away from the bore, the temperature fluctuations can’t be seen basically, and the temperature response shows a slow upward trend.

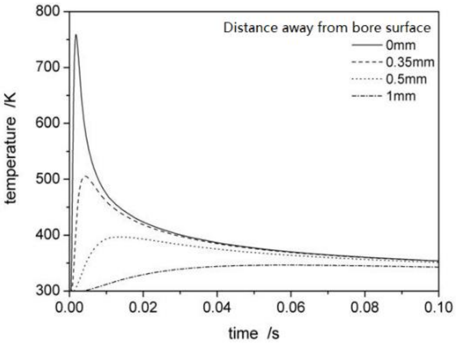
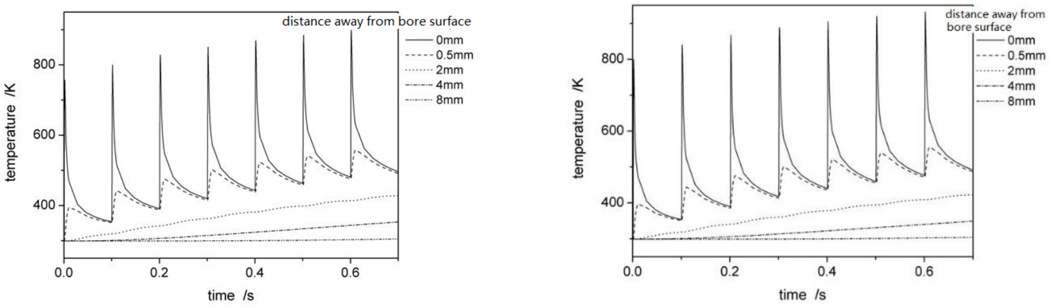


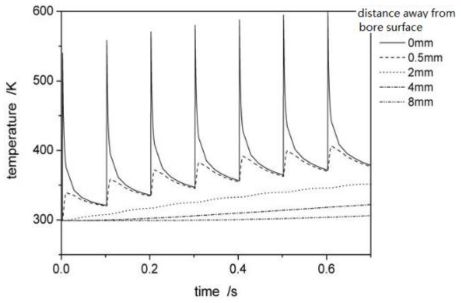
Fig.4 Temperature curve of single shoot (section A)

As shown in Fig.5, when firing continuously, the temperature response of the barrel 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. At the beginning of the rifling, the peak bore temperature increases 42.7K when the second bullet is shot. When the 7th shot is finished, the peak temperature increases only 13.9K from the end of the 6th shot. The temperature changes of the gun barrel bore at different axial sections are similar. However, the peak temperature values have differences, as shown in Fig.5(b) and Fig.5(c). At the 1th shot, the peak temperature value in section B is 798.9K, and the peak temperature value in section C is 540.1K. The difference between section B and section C is 258.8K.

Fig.6(a) shows the temperature distribution at the maximum chamber pressure cross-section. With the number of shoot increases, the temperatures of cross-section points rise, but are not synchronous. Fig.6(b) shows the temperature distribution at muzzle region when continuously firing. With the number of shoot increasing, the temperature value at each point appears in the changes of rising basically synchronously. This temperature change with shoot number is obviously different between Fig.6(a) and Fig.6(b), 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 outer surface of barrel, and the temperature of outer surface point simultaneously increases.

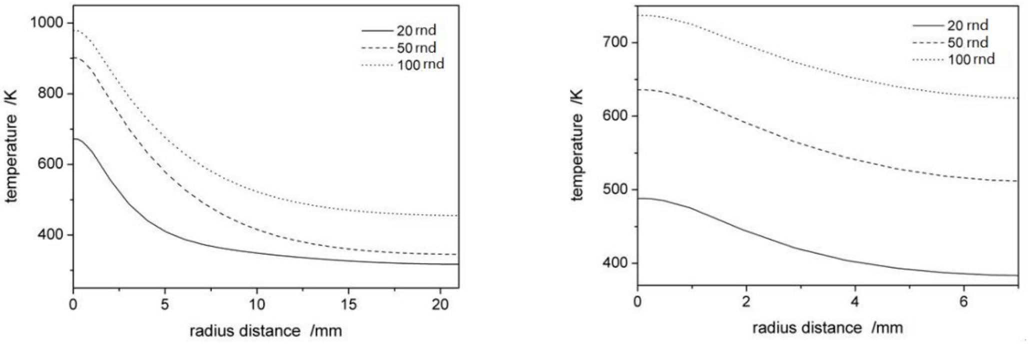


(a) Section A (b) Section B



(c) Section C

Fig.5 Variation of temperature in different sections when firing continuously



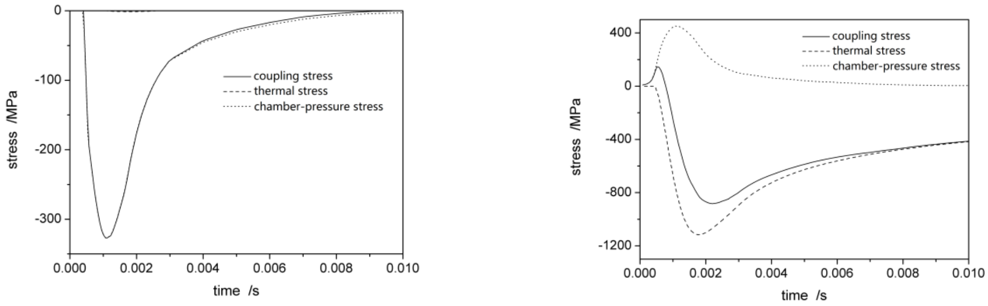
(a) Section B (b) Section C

Fig.6 Effect of thickness on heat flow when firing continuously

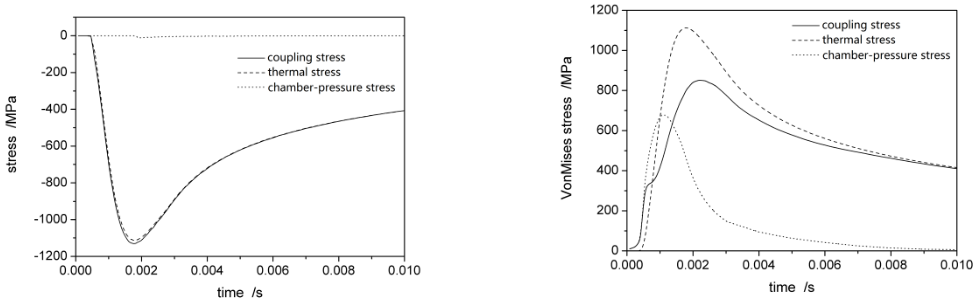
4.2 The Transient Stress of Barrel

For the case of single shot, as pressure and thermal loads are enforced both together and respectively, the transient stress obtained numerically at section A is demonstrated in Fig.7.

As shown in Fig.7(a), the time courses of chamber-pressure and coupling stresses are almost coincident, and thus the radial stress is mostly dominated by chamber-pressure stress. From Fig.7(b), it can be seen that the circumferential stress is composted of tension stress and compression stress. The tension and compression stresses are respectively caused by chamber pressure and thermal loads, and the peak value of thermal stress is higher than that of chamber-pressure stress. Therefore, a faint tension-stress pulse emerges firstly, and shortly the thermal stress grows dominant. For the emergence of tension stress, the coupling stress is less than the thermal stress. It can be found out from Fig.7(c) that the thermal stress is dominant axially, for the coupling and thermal stresses are coincident as a whole. For the coupling stress, the axial and circumferential components are more dominant than the radial component, and also they are mostly affected by the thermal load, and thus the coupling stress is primarily dominated by the thermal stress. Based on Fig.7(d), it can be drawn that the coupling stress is mostly influenced by chamber-pressure load firstly, and then shortly influenced by thermal load. Because of the thermal load, the peak value of coupling VonMises stress is remarkably higher than the peak value of stress only caused by chamber-pressure load, while smaller than the peak value of thermal stress.



(a) Radial stress (b) Circumferential stress



(c) Axial stress (d) VonMises stress

Fig.7 Transient stress on inner surface at section A

As shooting continuously, the coupling VonMises stress on inner surface of barrel pulses (illustrated in Fig.8(a)). Because of the coupling effect of chamber-pressure and thermal loads, the coupling-stress amplitude is less than the thermal-stress amplitude, while the absolute value of coupling stress is bigger. For instance, the coupling VonMises stress respectively attains 1010.7MPa, 1100.9MPa and 1306.7MPa as firing the 1st, 2nd and 7th shot at section B. Still at section B, the coupling VonMises stress on interface between steel body and chrome layer respectively attains 596MPa and 1095MPa as firing the 1st and 7th shot (demonstrated in Fig.8(b)).

(a) On inner surface of chrome layer (b) On interface between steel body and chrome layer

Fig.8 Coupling VonMises stress at sections when firing continuously

5. Conclusions

(1) A thermal-solid coupling FEA model of large-caliber barrel is built up and verified. The transient temperature and stress field of the barrel under the effect of both periodic pressure and heat shock are

calculated. The models as well as the analytical methods employed here are useful for the design of gun barrel.

(2) The computational results show that the large caliber gun bore surface temperature is shaped pulse. When shooting continuously, the pulse peak rises rapidly firstly and then slows down gradually. Thermal load caused the thin-layer effect significantly and the exquisite change region focuses on the thin inner wall of bore. The estimation and improvement of large caliber gun barrel life must consider the transient temperature data.

(3) The computational results show that the coupling action of thermal shock and pressure pulse has great effect on the transient stresses of barrel. For radial stress, the chamber-press induced stress is dominant; while for axial stress, the thermal induced stress is dominant. In addition, the hoop stress is the coupling actions of the chamber-pressure load and thermal load. The large caliber gun barrel strength design should consider the coupling action of thermal shock and pressure pulse.

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References

[1] M.L. Bundy, N. Gerber, J.W. Bradley: Gun barrel erosion and bore temperature modeling, Summer Computer Simulation Conference (1993), Boston, Massachusetts, USA, p. 397-402.

[2] B. Lawton: The influence of additives on the temperature, heat transfer, wear, fatigue life, and self ignition characteristics of a 155 mm gun, Journal of Pressure Vessel Technology, vol. 125 (2003), p. 315-320.

[3] E. Petitpas, B. Campion: Crack propagation in a gun barrel due to the firing thermo-mechanical stresses, Journal of Pressure Vessel Technology, vol. 125 (2003), no. 3, p. 293-298.

[4] C. Xu, Y.H. Wu, X.R. Guan: The transient stress and life analysis of a gun tube, ASME 2014 Pressure Vessels & Piping Conference, Anaheim, California, USA.

[5] Y.H. Wu, C. Xu: Analysis of the temperature field of a large-caliber machine gun tube based on thermal-solid coupling, 25th International Symposium on Ballistics (2010), Beijing,China.

[6] D. Boisson, C. Grignon: 1D and 2D thermal modeling of the heating and the cooling of a gun barrel during a burst, 14th International Symposium on Ballistics (1993), Quebec, Canada, p. 371-380.

[7] H.L. Lee, Y.C. Yang, W.J. Chang: Estimation of heat flux and thermal stresses in multilayer gun barrel with thermal contact resistance, Applied Mathematics and Computation, vol. 209 (2008), No. 2, p. 211-217.

[8] Y.H. Wu, C. Xu, F. Li: Analysis of the temperature field of a large-caliber machine gun tube based on thermal-solid coupling, Journal of Nanjing University of Science and Technology, vol. 31 (2007), No. 1, p. 1-5. (In Chinese)

[9] Y.H. Wu, C. Xu, H.B. Zhang: Dynamic response analysis of transient thermoelasticity couple of a large-caliber machine gun barrel, Journal of Ballistics, vol. 18 (2006), no. 4, p. 16-20. (In Chinese).

[10] S.C. Kerwien, R. Rocha: Metallurgical failure analysis of the M230 machine gun barrel-MIF-A -001-1999-I, ARWEC-TR-99002, US Army Armament Research, Development and Engineering Center.

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