Analysis on the Radial Friction Thermo Genesis of the Projectile-loaded equipment

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Abstract. According to the heat sensitive of projectile-launched plex equipment made by the PE, the ballistic radial friction condition is analyzed. The numerical analysis model of the rotary sliding friction relative speed between the plex equipment and the projectile body is setup. Based on the numeric calculation results, the rotary sliding friction relative speed time curves are plotted. The temperature distribution model of plex equipment surface sliding friction was studied by the classical heat-transfer theory. The simulation results indicate that the sliding friction heat is the major factor of the distortion for the over-heated.

Introduction

Spin-stabilized projectile during launch withstand great radial inertia force and tangential inertial force, the radial inertia force directly produce expansion of the filling material[1], under normal circumstances, the load and the support tile fixed connection, so tangential inertial force could be ignored. When load could not be fixed with supporting tile, the inertia force will cause the load and the support tile generate sliding friction and thereby produce large amounts of heat in a short time. The projectile-loaded equipment is the core devices of artillery passive interference decoy[2], It needs to expand after thrown from the bomb body, unable to fixed with support tile, while its main support structure molded from polyethylene material composition. The thermal deformation of polyethylene support structure will lead to serious distortion of the mission equipment reflection characteristics; reduce the performance of target simulation of the projectile-loaded equipment.

To ensure that the structure of polyethylene will not Thermal deformation in the process of firing, we must analyze the friction and heat of the rotation of the projectile-loaded equipment； First, based on the full-ballistic missile body rotating radial force environmental characteristics, theoretical analysis of the relative rotational speed between the equipment and cartridge , given its numerical calculation model. Then establish rotational friction and heat energy conservation model, using numerical simulation analysis of friction and heat caused by friction surface temperature rise; finally put forward measures which can reduce rotating friction and heat between equipment and cartridge. And test shows that it can effectively reduce the friction surface temperature rise.

Projectile-loaded Equipment Rotation Modeling

Projectile Rotation Model

In the process of launch, projectile-loaded equipment with the projectile moves with high-speed in the interior pressure effect. On the effect of rifling, stabilize the rotation of the projectile, result in high-speed rotational movement. Ballistic projectile within [3], by the relationship with the projectile angular velocity and the linear velocity, we have:

$$\Omega = \frac{v \tan \alpha}{r} \tag{1}$$

And, α is rifling wrapped around the corner, r is projectile radius.

Using the classical trajectory equations, ballistic speed can be list (polynomial data fitting):

$$\ddot{x}_r = 8.8074\times10^{20}t^7 - 3.65\times10^{19}t^6 + 5.747\times10^{17}t^5 - 4.108\times10^{15}t^4 + 1.135\times10^{13}t^3 + 7.959\times10^{8}t^2 - 6.941\times10^{6}t + 731.852 \quad (2)$$

Substitute (1) into (2), we have any time t for interior ballistic missile rotation speed:

$$w_1(t) = 1.7232\times10^{20}t^8 - 8.2639\times10^{18}t^7 + 1.5442\times10^{17}t^6 - 1.3634\times10^{15}t^5 + 5.0743\times10^{12}t^4 - 1.6141\times10^{9}t^3 - 2.4020\times10^{6}t^2 - 679.6835t + 0.1828 \quad (3)$$

Through the speed of the projectile ballistic line, we get angular velocity curve which described in Fig. 1.

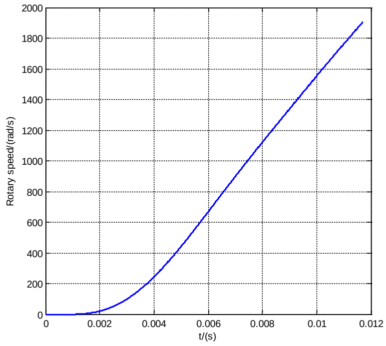

Fig.1 The projectile rotary speed time curve in the interior ballistic

It can be seen that the angular velocity of the projectile can achieve more than 1800rad/s.

The law of rotation angular velocity attenuation when the rotating projectile in outer ballistic phase has an important role in the design and research of the fuse, projectile and ballistic has been recognized as the amended soft Gerry the (E. Roggla) formula[4] having a better accuracy. Sophie Gerry revised formula expression:

$$w_1(t) = w_g \exp\left(-0.4\frac{LD^3}{A}t\right) \quad (4)$$

And, w is the projectile rotation angular velocity of the corresponding time t (rad/s), w_g is the rotation angular velocity of the projectile muzzle (rad/s), L is the projectile full-length (m), D is the projectile radius (m), A is projectile polar moment of inertia ($kg\cdot m^2$)

Projectile-loaded Equipment Rotation Model

When the projectile rotation angular acceleration increases to a limit value, i.e. the angular momentum delta is greater than the static friction between the bullet and the cartridge, relative rotation will occur between the bullet and the cartridge. By the law of conservation of angular momentum that:

$$\vec{M} = \vec{R}\times\vec{F} = J\frac{dw}{dt} \quad (5)$$

Where $\vec{R}\perp\vec{F}$, we can get $\vec{R}\times\vec{F} = F\cdot R$ and $J = \frac{1}{2}mR^2$.

The criterion for rotation angular acceleration of Projectile cartridge occurs relative rotation: when $\frac{dw}{dt} > \frac{2F_j}{mR_z}$, Produce relative sliding between the projectile and the cartridge, and $F_j = f_jP$, f_j is static friction-factor, P is the pressure between the projectile and the cartridge.

Assumed to occur relative sliding moment is t_h, rotation speed is w_h, the sliding friction between them constantly is $F_d = f_dP$, the projectile bait angular acceleration constant $2F_d/mR_z$.

Hen arbitrary time t, the rotational speed of projectile bait is

$$w_2(t) = \frac{2F_d}{mR_z}(t - t_h) + w_h \quad (6)$$

And R_z is projectile radius, m is the quality of the projectile.

From the above analysis the rotation velocity of the projectile full ballistic curve can be shown in Fig. 2. It can be seen, when the dispersion ballistic reach same rotation speed with the bullet out of the muzzle, the rotation speed reduce slowly. After the end of the cartridge with the rotation of the projectile, the rotation speed of Bullets increases linearly. The relative rotation time between the bullet and the cartridge is close to 25ms, the maximum difference of the relative velocity of the rotational angular velocity of more than 1000rad/s.

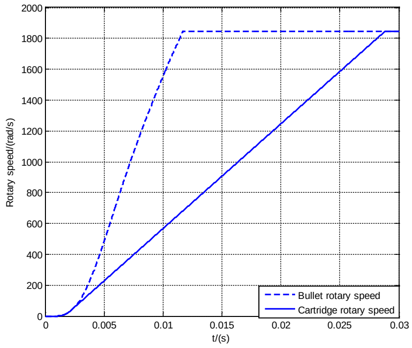

Fig.2 The rotary sliding friction relative speed time curve plot in the ballistics

Rotary Heat Analyses

Physical Model of Rotary Heat

The sum of the frictional force acting $q = f \cdot p \cdot \Delta v$ is equal to the heat of projectile-loaded equipment and support tile generated. Where the pressure of the projectile-loaded equipment and support tile is p, the friction coefficient is f, the relative velocity between the support tiles with projectile-loaded equipment is Δv. The lateral pressure of the projectile-loaded equipment mainly Determined by loading stress between projectile-loaded equipment and support tile. Establish energy conservation equation of support tile and projectile-loaded equipment, make the following assumptions: in the entire process of Launch, the thermo-physical parameters of supporting tile and projectile-loaded equipment (thermal conductivity, density, heat capacity) don't change over time; projectile-loaded equipment don't have internal heat source, the heat is mainly generated by the friction of the shell and projectile-loaded equipment. According to the above conditions, we can get the energy conservation equation of support tile：

$$\frac{\partial T_1}{\partial t} = \alpha_1 \frac{\partial^2 T_1}{\partial x_1^2} \text{ and } \alpha_1 = k_1 / \rho_1 c_1 \tag{7}$$

Energy conservation equation for projectile-loaded equipment：

$$\frac{\partial T_2}{\partial t} = \alpha_2 \frac{\partial^2 T_2}{\partial x_2^2} \text{ and } \alpha_2 = k_2 / \rho_2 c_2 \tag{8}$$

And the density is ρ ($g \cdot cm^{-3}$); specific heat capacity at constant pressure is c ($J \cdot g^{-1} \cdot K^{-1}$); k ($W \cdot cm^{-1} \cdot s^{-1} \cdot K^{-1}$) is thermal conductivity.

Determine the Initial and Boundary Conditions

The incoming heat to shell is q_1. The incoming heat to explosives is q_2. Without considering other energy losses, and that the frictional heat is generated all incoming shell and explosives, we can have $q = q_1 + q_2$.

The boundary conditions for：

$$\text{If } x = 0, t > 0 \text{ then } k_1 \left| \frac{\partial T_1}{\partial x} \right| = 0 \tag{9}$$

$$\text{If } x=\delta\,,t>0 \text{ then } \begin{cases} k_1\left|\dfrac{\partial T_1}{\partial x}\right| = q_1 \\ k_2\left|\dfrac{\partial T_2}{\partial x}\right| = q_2 \end{cases} \quad T_1 = T_2 \tag{10}$$

$$\text{If } x=\delta+h\,,t>0 \text{ then } k_2\left|\frac{\partial T_2}{\partial x}\right| = q_2 \tag{11}$$

From (11), we can get

$$q_1 = \frac{q}{1+\dfrac{k_2}{k_1}\sqrt{\dfrac{\alpha_1}{\alpha_2}}}\,,\ q_2 = \frac{q}{1+\dfrac{k_1}{k_2}\sqrt{\dfrac{\alpha_2}{\alpha_1}}} \tag{12}$$

Initial conditions：

$$T = F(x) = 20^{\circ}C\,,0 \le x \le L\,,t=0 \tag{13}$$

With above, the temperature rise of the friction could be calculated. The temperature rise of the friction surface is

$$\Delta T = 1.13\frac{f\cdot p\cdot \Delta v\sqrt{t}}{\sqrt{\rho_1 c_1 k_1}+\sqrt{\rho_2 c_2 k_2}} \tag{14}$$

To be seen, the temperature increases of friction interface in direct proportion to friction coefficient f, surface of the stress p and the relative velocity Δv and t. Consider the temperature increases between projectile-loaded equipment and support tile, Density, specific heat and thermal conductivity of projectile-loaded equipment and metal is fixed, and related to the surface of the act stress, relative velocity, friction coefficient and friction time.

Numerical Analysis and Experimental Verification

Equation (8) - (14) is the mathematical description of the projectile-loaded equipment rotary friction and heat , this partial differential equations apparently belong to the second initial condition problem (Neumanm conditions), it can be used a four-point explicit differential format for its numerical solution. Derivative boundary conditions approximate to the central difference, and using a form of four-point explicit difference denote partial differential equations, simplified the form of equations, we can get:

$$\begin{bmatrix} T_0^{n+1} \\ T_1^{n+1} \\ \vdots \\ T_N^{n+1} \end{bmatrix} = \begin{bmatrix} 1-2r & 2r & & \\ r & 1-2r & r & \\ & \ddots & \ddots & \ddots \\ & & 2r & 1-2r \end{bmatrix} \begin{bmatrix} T_0^{n} \\ T_1^{n} \\ \vdots \\ T_N^{n} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 2r\Delta x\dfrac{q_1}{k_1} \end{bmatrix} \tag{15}$$

And, $r=\dfrac{\alpha\Delta t}{\Delta x^2}$, $\alpha = k/\rho c$, Δt is time step; Δx is space step, Stable condition is $r=\dfrac{\alpha\Delta t}{\Delta x^2}\le\dfrac{1}{2}$. By solving the equations of the supporting tile and projectile-loaded equipment, we can get the temperature distribution in the different time.

Table 1 Performance parameters of different materials

Materials	Density	Specific Heat	Thermal Conductivity
PE	30	1340	0.04
Steel	213	654	649

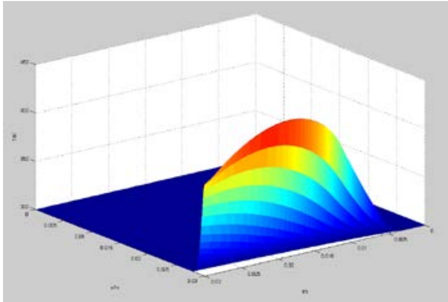

Fig. 4 Spatial temperature distribution in shell

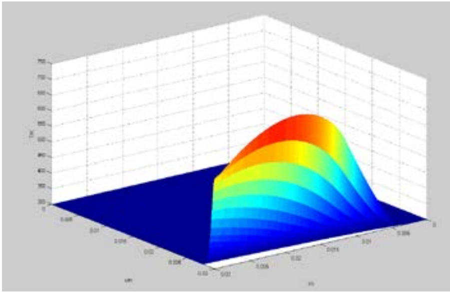

Fig. 5 Spatial temperature distribution in plex equipment

The time of relative rotation less than 25ms, the maximum value of the relative rotational speed between projectile-loaded equipment and cartridge exceeds 1000rad/s. As can be seen from Fig. 4 and Fig. 5, since the generating relative rotation time is too short, which makes the large amounts of heat is gathered on both sides of the friction surface, causing the temperature of the mission equipment is too high, the temperature exceeds 700K, far exceeds the temperature limit of the heat deformation of the polyethylene-based material. It can be seen from Figure 4, the cartridge of the steel material enhance the friction heat conduction, may be appropriate to reduce the process of the friction heating, so that the frictional heat rate lowering, so that the heat can be thermal conduction through cartridge, thus reducing hot spots of friction surface on the equipment.

Conclusions

This thesis introduce the physical process of the projectile-loaded equipment occurred relative rotation with cartridge in a detailed analysis, established energy conservation equations and simulation analysis by using finite difference method. The simulation results indicates that the sliding friction heat is the major factor of the distortion for the over-heated. Therefore when design the structure of such projectile-loaded equipment, we should take into account how to reduce the heat generated by the rotating friction. The available measures which can take to reduce friction and heat list as follows：(1) Take radial bearing reduce rotational acceleration, using the friction of bearing to absorb the heat that generated in the rotation process; (2) Using added lubrication, longer duration of action, take steel material projectile to enhance the effect of heat conduct.

According to mechanism of friction overheating and spin velocity, we developed principle prototype on the basis of related research, and experimented launch test. For the test results: less spin, lower friction, can effectively solve the hot spots on the surface which caused by the sliding friction heat.

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