THERMO-MECHANICAL COMPUTATION IN A 120-MM CHROMIUM-COATED GUN BARREL WITH APFS-DS WITH WEAR-REDUCING ADDITIVES

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This paper describes the calculation of the parietal temperatures and thermo-mechanical stresses in a 120-mm chromium-coated gun barrel with Armour Piercing Fin Stabilize Discarding Sabot (APFS-DS) with wear-reducing additives. We consider in this study that the wear-reducing film material is attached on the surface of the bore.
First we present software that computes pyrolysis processes in film material when hot internal ballistics propellant gases heat it.
A numerical parametric study is then conducted, to determine the sensitivity of the barrel heating and cooling to the protective film thickness and to the Arrhenius's correlation parameters.
The comparison between computation and parietal temperature measurements shows a good agreement: with 10 μm thickness of TiO2 as wear-reducing additives located on the chromium inner wall, the maximal value of the steel/chromium interface temperature is reduced (more than 100°C near the forcing cone).
Thermo-mechanical computations for APFS-DS with TiO2, compared to APFS-DS, show that the compressive tangential stresses decrease (gradient and amplitude) within the chromium coating thickness and that the fast traction-compression cycle of the interface tangential stresses gets slower with time.
So APFS-DS ammunition with TiO2 as wear-reducing additives will reduce and delay the gun barrel thermal erosion significantly.

INTRODUCTION

This work deals with the calculation of the parietal temperatures and thermo-mechanical stresses in a 120-mm chromium-coated gun barrel with Armour Piercing

Fin Stabilize Discarding Sabot (APFS-DS) with wear-reducing additives. The French State (DGA/SPART) sponsors this work.

In order to realize such study it's necessary to have physical model describing pyrolysis processes in film material when hot propellant gases heat it, and to conduct a numerical parametric study to determine the sensitivity of the barrel heating to the protective film parameters.

Then a comparison with parietal temperature measurements is made.

Finally we present the computation results with ABAQUS code of the steel/chromium interface tangential stresses caused by gas temperature and pressure.

COMPUTATION OF THERMAL-PROTECTIVE FILM

Physical and Numerical Studies: PYROLYSE code

When firing, the protective film material is heated and sometimes pyrolysed: the pyrolysis products move along the bore surface. We consider here that the film is attached on the surface of the bore. Under the action of high gas temperature the film material is expected to pyrolyse, accompanying structure and phase changes, heat effects and injection of pyrolysis vapour into exterior powder gas flow. During pyrolysis the heat physical properties of a film's material are a function of the temperature.

The problem of film ablation is generally limited to the thermal conductivity in a "five-layer wall" [1]:

- First and second layers are respectively the barrel steel and chromium coatings.
- Third layer is a part of the film material without any phase or structure changes. With time the film is gradually decreased.
- Fourth is the pyrolysis zone, where phase or structure change takes place with internal sources of heat. Inside this zone, some parts of the film material transit into gas phase and the other part is carbonized to form a charred layer. This layer is considered as a porosity structure.
- Fifth layer is a charred layer, where all the chemical reactions of pyrolysis are over. Pyrolysis gases issued from fourth layer are crossing this charred layer to be injected in combustion gases of the propelling charge in the bore. The presence of an injection effect from pyrolysis gases results in a decrease of heat transfer coefficient to film surface. The heat transfer coefficient resulting from the combustion of the propellant charge is determined by using MIGAPPAC code [2] that computes the boundary layer at the gas/wall interface; this code is connected to an internal two-phase flow and adiabatic code, during the shot. It’s important to use a time step as little as

possible if we want a satisfactory accuracy of the calculated temperature. This internal ballistics code enables us to determine the gas temperature. After the projectile exit, we used the cooling phase modulus of the MECCAD code [2].

At location X from the breech the ablation is calculated with a radial 1-D unsteady finite difference conduction code. There are two sources of heat terms in the conduction equation: one characterises the heat absorbed by pyrolysed gas, the other characterises the heat produced by pyrolysis. The gas pyrolysis rates depend of the fraction of film material converted into gas. The temporal derivative of this fraction of film material converted into gas has an exponential dependence on the inverse of the temperature and is a function of Arrhenius's parameters (activation energy, rate coefficient).

Data inputs of this code are: materials thickness; steel, chromium, film, carbon and pyrolysis gases physical properties; film chemical inputs.

Numerical Parametric Study

A numerical parametric study with this code named PYROLYSE is conducted, in the case of a 120-mm chromium-coated gun barrel and in a section near the forcing cone, to determine the sensitivity of the barrel heating and cooling to the protective film thickness and to the Arrhenius's correlation parameters (activation energy, rate coefficient). We supposed, concerning this parametric study, that the protective film is a Wax or a Polythene film: its melting temperature is near 100°C.

Film thickness (μm)	Pyrolysed film thickness during the shot	T chromium inner wall (K)	T chromium/steel interface (K)
0			1300
25	100%	1465	1115
50	100%	920	620
100	80% at the end of the shot	310	300

Table 1. Sensitivity of the maximal barrel parietal temperature to the film thickness (with an activation energy of 100000 J/mol & a rate coefficient of 10^9 s^{-1})

Rate Coefficient (s^{-1})	T chromium inner wall (K)	T chromium/steel interface (K)
10^9	1465	1115
10^{12}	1480	1130
10^2	1345	990

Table 2. Sensitivity of the maximal barrel parietal temperature to the rate coefficient (with a protective film thickness of 25μm & an activation energy of 100000 J/mol)

Activation Energy (J/mol)	T chromium inner wall (K)	T chromium/steel interface (K)
100000	1465	1115
350000	1325	980
50000	1485	1135

Table 3. Sensitivity of the maximal barrel parietal temperature to the activation energy (with a protective film thickness of 25μm & a rate coefficient of $10^9 s^{-1}$)

This numerical parametric study shows, for a 25 μm film thickness, that:
- When the rate coefficient value varies from 10^9 to 10^{12} the maximal steel/chromium interface temperature increase is 15°C,
- When the activation energy value varies from 100000 to 350000 the maximal steel/chromium interface temperature decrease is above 100°C. If the value of the activation energy is 50000 this interface temperature increases,

We also realized a numerical study to determine the sensitivity of the barrel heating to the film density and heat capacity:
- When the film density increases (from 950 to 3000 kg/m^3), the maximal steel/chromium interface temperature decreases,
- When the heat capacity increases (from 1750 to 2500 J/kg/K), the maximal steel/chromium interface temperature decreases.

Calculation of the 120-mm chromium-coated gun barrel temperature with APFS-DS without wear-reducing additives

To compute the thermal behaviour of the 120-mm chromium-coated gun barrel with APFS-DS, during a shot without wear-reducing additives, we used the MECCAD code [2].

THERMO-MECHANICAL COMPUTATION IN A 120-MM CHROMIUM-COATED GUN BARREL WITH APFS-DS WITH WEAR-REDUCING ADDITIVES

Temperature Measurements

The tests were carried out at ETBS (Etablissement Technique de Bourges) on February 1999, with a 120-mm chromium-coated test gun barrel [3]. The tube length is about 6 m. There was no wear on this tube before the tests. The shots were realized with inert APFS-DS projectile (without and with 230 g of TiO2 (47%) and Wax (53%) wear-reducing additives in the propellant charge). We used a double base propellant.

Due to the very steep temperature gradients present near the inner surface of the gun barrel, the measuring holes are drilled so as to set the sensors at the shortest distance from this surface. For the section located at 1,300 mm from the breech, the closest distance that could be practically located without destruction due to internal pressure is 630 μm with an accuracy of ± 10 μm. Others thermocouples are located at 830 and 930 μm from the inner wall. Temperatures were measured using intrinsic iron/constantan thermoelectric sensors.

Wear-reducing additives efficiency

The additives were located around (150g) and at the top of the charge (80g). The analysis of the temperature measurements shows us a good thermal efficiency of ammunitions with additives and with a small decrease of the gun performances (the projectile velocity decrease is about 1%).
The temperature decrease (compared with the ammunition without additives) is about 3% to 4% for this section located at 1,300 mm from the breech. Experimental steel/chromium interface temperature was determined using an inverse conduction calculation method [3]: its decrease ranges between 100 to 150°C.

Temperature Calculations and Comparison with Experimental Results

The comparison with calculations shows the efficiency of the additives "Figure 1": with 10 μm thickness of wear reducing additives (TiO2) on the chromium inner wall, the maximal value of the steel/chromium interface temperature is reduced (more than 100°C): this temperature decrease should be enable to delay and/or to reduce the chromium and steel structure changes. At 630 μm from the inner wall, the calculated temperature decrease (compared with the ammunition without additives) is about 4%. The same decreases were observed during the trials (see the above paragraph): so our calculation is validated.

We considered here that TiO2 was the major protective film component: 78% [4]. That's why we take into account a 10 μm TiO2 thickness located uniformly along the tube length.

The melting temperature value of the TiO2 is about 1850°C and there was no pyrolysed film during the shot by using the PYROLYSE code.

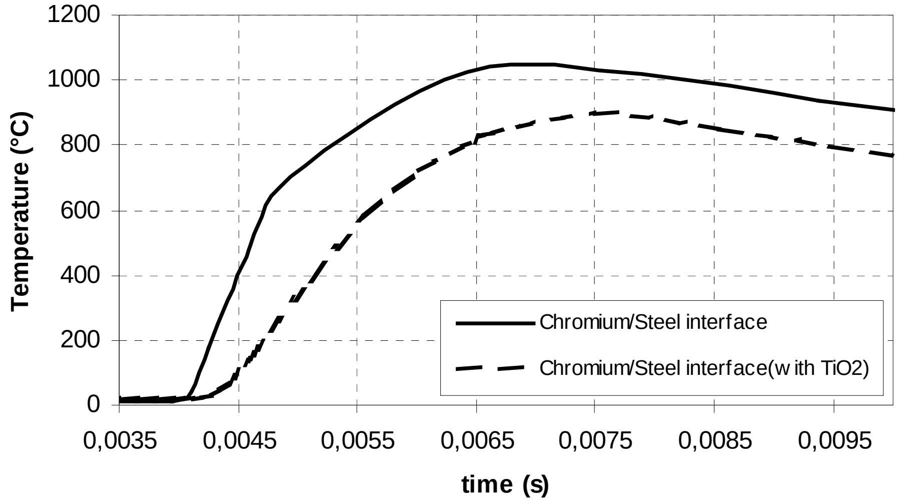

Figure 1. Barrel parietal temperature computation with APFS-DS without and with wear reducing additives (TiO2): chromium/steel interface temperature with time (near the forcing cone)

The temperature gradients inside the chromium coating thickness are more important for APFS-DS without wear-reducing additives: twice as big as those of APFS-DS with TiO2 (at the time corresponding to gas pressure maximum). And the inner wall chromium temperature value for APFS-DS with TiO2 decrease significantly.

So APFS-DS with TiO2 will reduce and/or delay the gun barrel thermal erosion.

Thermo-mechanical Computation

Here we present the computation results, using the ABAQUS code, of the steel/chromium interface tangential stresses caused by the gas temperature and pressure during the shot of a 120mm gun barrel with APFS-DS without and with wear-reducing additives (TiO2).

The calculation is 2D axisymmetric: the auto-frettage and plasticity of the steel are not considered here. The chromium and steel thermal properties vary with the temperature. The steel mechanical properties vary also with the temperature.

Thermo-mechanical calculations with ABAQUS code show (see "Figure 2"):

- A fast traction-compression cycle (at the interface) in the cross section located at 1,300 mm from the breech. The maximal gas pressure time takes place before the maximal inner wall temperature time: that's why we get traction tangential stresses before compressive ones.

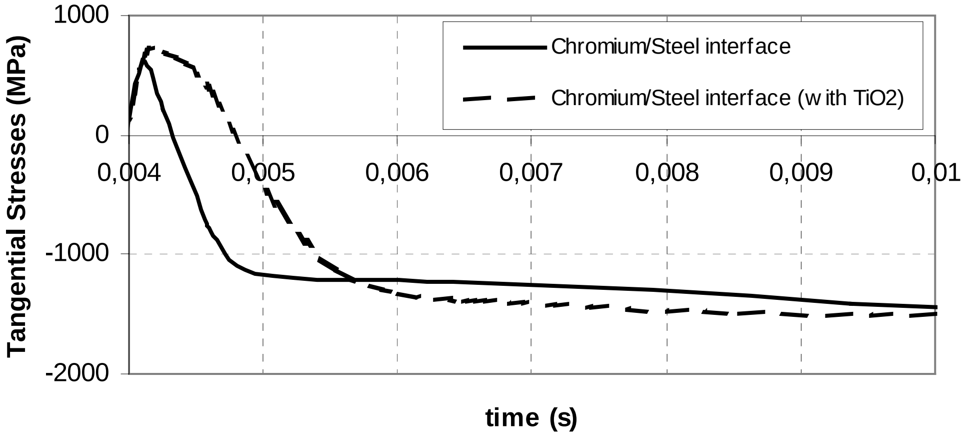

Figure 2. Thermo-elastic computation with APFS-DS without and with wear-reducing additives (TiO2): chromium/steel interface tangential stresses with time (near the forcing cone)

- High compressive tangential stresses due to the temperature effect [5]: their values are near the yield-stress of steel. With 10 μm thickness of wear reducing additives (TiO2) on the chromium inner wall, the fast traction-compression cycle of the interface tangential stresses gets slower.

Stress gradients are also reduced inside the chromium coating thickness. At the time when the gas pressure is maximal, the tangential stress gradient is more important for APFS-DS without wear-reducing additives: three times as big as APFS-DS with TiO2 one. There is an important discontinuity at the steel/chromium interface, which is caused by the difference between the values of the chromium Young's modulus and the steel Young's modulus.

More generally compressive tangential stresses are decreasing (gradient & amplitude) within the chromium coating thickness for APFS-DS with TiO2.

When the auto-frettage and the plasticity of the steel are considered the above conclusions are quite the same but the tangential stresses traction-compression cycle (at the interface) is totally negative. The traction stresses level decreases and the maximal compressive tangential stresses are under the yield-stress of steel.

CONCLUSION

The PYROLYSE code enables us to compute the heating and the cooling of a 120-mm chromium-coated gun barrel, firing APFS-DS projectile with wear-reducing additives during a shot. Now, it's also possible to optimize the wear-reducing material components: of course we must know the film material chemical inputs and its physical properties.

The comparison between computation and parietal temperature measurements (630, 830 & 930 μm from the inner wall), for the section located at 1,300 mm from the breech, shows a good agreement: with 10 μm thickness of TiO2 as wear-reducing additives, located on the chromium inner wall and near the forcing cone, the maximal value of the steel/chromium interface temperature is reduced (more than 100°C): this temperature decrease should be enable to delay and/or reduce the chromium and steel phase or structure changes.

Thermo-mechanical computations show that the compressive tangential stresses decrease (gradient and amplitude) within the chromium coating thickness for APFS-DS with TiO2 as wear-reducing additives and that the fast traction-compression cycle of the interface tangential stresses gets slower with time.

So APFS-DS ammunition with TiO2 as wear-reducing additives will reduce and/or delay the 120-mm chromium-coated gun barrel thermal erosion.

The next step of our work will concern the calculation of the heat flux due to the projectile band friction on the inner wall, in order to improve the calculation code accuracy when we move further away from the forcing cone [2].

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