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PLASMA IGNITION OF CONSOLIDATED PROPELLANTS IN A 60-MILLIMETRE ETC GUN

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Firing experiments were carried out with an electrothermal-chemical (ETC) gun of calibre 60 mm using exploding wire plasma ignition initiated by the discharge of a capacitor bank (initial voltage 10 kV; plasma energy less than 1% of chemical energy). Charges of consolidated propellant JA2 with loading densities between 0.4 and 0.8 g/cm^3 yielded kinetic energies of the projectile which exceeded those achieved with conventional L1 by 20% to 25%, if compared at equal values of the maximum gas pressure in the combustion chamber. This increase is caused by the higher loading densities feasible with JA2. In order to improve the performance further, but still to avoid dangerous peak pressures, a variation of several parameters was studied: modification of the projectile, chemical treatment and composition of the propellant, amount of plasma energy, and time controlled plasma injection.

INTRODUCTION

The electrothermal-chemical (ETC) concept of ISL was defined in 1997 with the objective to improve the performance of large-calibre guns (120 mm and more), i.e. to increase the muzzle kinetic energy of the projectile [1]. Recently, the interest has extended to mid-size calibres as well. All similar programs which were proposed in the past must consider the constraints of limited combustion chamber volume, prespecified acceptable maximum gas pressure, restricted barrel length, critical erosion at higher gas temperature, and low-density storage of electrical energy.

In order to keep the effort and cost low, we started our first experiments with a modified conventional 20-mm gun using “direct” plasma ignition of consolidated propellant charges with loading densities up to 1.3 g/cm^3 [2]. This “direct” ignition, where the plasma produced by an exploding wire immediately interacts with a certain part of the propellant surface, proved to be more efficient than the “indirect” ignition by a guided plasma jet.

In the autumn 1999 we initiated the transfer of our promising findings with the small gun to a 60-mm ETC gun. This is, in fact, not a simple problem, since it is not possible

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just to enlarge the total charge configuration. From a safety point of view, considering the adverse environmental conditions on the proving ground, the high voltage of our power supply is limited to a lower level than in a closed firing hall.

EXPERIMENTAL ARRANGEMENT

The weapon is operated on the firing range of ISL, where the electrical high power supply is placed in a container near the gun and the controlling and recording units are installed in a bunker about 30 m away. The transmission of the measuring data is performed by electro-optical converters and fibre-optic links.

ETC Gun of 60 mm Calibre

The breech of a conventional gun (barrel length 2.85 m) was modified to accept a high-voltage feedthrough. A coaxial metal tube (outer diameter 22 mm) extends along the axis of the combustion chamber (volume 1932 cm^3), conducting the current pulse to three exploding wires (length 50 mm) mounted at its front end near the projectile.

Pressure transducers are inserted in the combustion chamber close to the projectile base, in the barrel near the initial position of the projectile, and at the muzzle. The maximum acceptable gas pressure in the combustion chamber is specified as p_{lim} = 550 MPa, though the gun can withstand higher values.

A full-calibre steel cylinder with a polyethylene obturating band, supported by a thin transition steel cone, is used as our “standard” projectile (mass m_p = 3.0 kg).

High-Voltage Power Supply

The plasma produced by the exploding wires is initiated by the discharge of a capacitor bank which is composed of several modules with thyristor switches and pulse forming coil inductances. They may be triggered simultaneously or consecutively with a precise time delay. The initial voltage of 10 kV results in 43 kJ of electrical energy stored per module, up to 60% of which will typically be injected into the plasma within less than 2 ms.

During each firing, the variation of the plasma current $I_P(t)$ and of the voltage across the electrodes $U_P(t)$ is recorded. From these signals the plasma properties like the resistance and the injected power are calculated as a function of time afterwards, as well as the total injected plasma energy E_P, which in most cases remains below 1% of the chemical energy released by the combustion of the propellant.

Charge Configuration

We have carried out a large number of firings using our “standard” charge configuration which consists of several propellant disks (outer diameter 90 mm, central bore 25 mm, thickness 20 to 40 mm) with an average density of 1.4 g/cm^3. These disks are consolidated from grains of JA2 (equivalent: L 5460; 7 perforations; diameter 6.5 mm, length 9.8 mm, web 1.2 mm; heat of combustion Q_{ex} = 4.7 MJ/kg). A definite number of these disks are mounted on the pulse-conducting tube mentioned above, so that the plasma ignition is initiated inside the front part of the total charge, near the projectile. Variations of this type of charge will be described later.

RESULTS AND DISCUSSION

At the beginning of our investigation we compared the firing performance of our "standard" charge configuration with a conventional reference charge. Afterwards we studied several measures in order to mitigate high peak pressures and to avoid dangerous pressure waves inside the combustion chamber.

Comparison of Consolidated Propellant with Conventional Charge

During a comprehensive firing series with the "standard" charge configuration the loading density Δ of the consolidated propellant JA2 was gradually increased from 0.4 up to 0.8 g/cm^3. Using one or two modules of the capacitor bank, the injected plasma energy E_P did not exceed 50 kJ.

The kinetic energy E_{kin} of the "standard" projectile is presented in Fig. 1 (circles) as a function of the maximum gas pressure p_{max} in the combustion chamber. The values of Δ are indicated as parameters in the diagram. Even with the highest loading density, which yielded the peak pressure p_{max} = 750 MPa, the pressure history remained relatively smooth and did not show marked pressure waves.

Additional tests with the very low loading density of only 0.15 g/cm^3 helped to find an empirical regression function of the form

$$E(kin) = a\,(p_{max} - p_0)^b \tag{1}$$

With its three parameters a, b, and p_0, it fits the measured data very well (linear correlation coefficient R = 0.995) and yields the pressure of extrusion p_0 (43.8 MPa (Fig. 1).

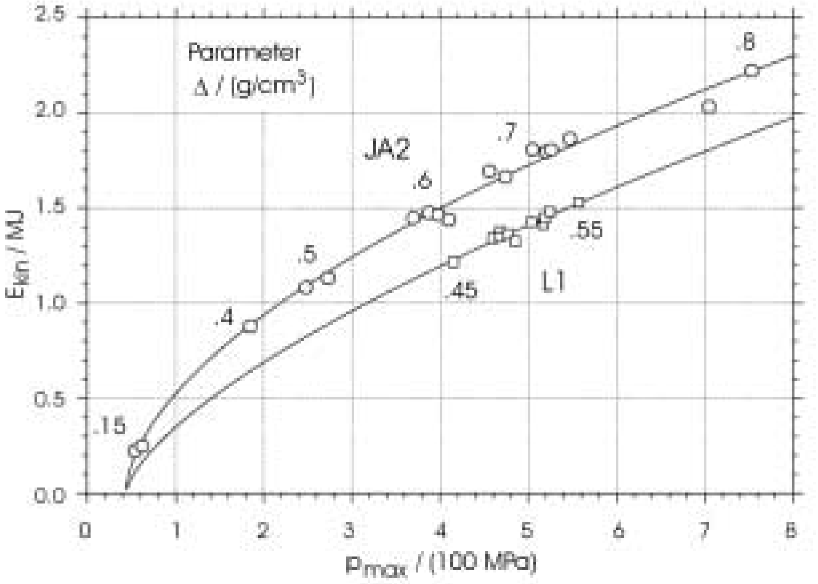

Figure 1: Firing performance of JA2 compared with L1.

It should be stressed that conventional ignition could not create sufficient combustion of the consolidated charges. This had already been demonstrated in the case of the 20-mm gun, even under more favourable conditions [2].

As a reference for comparison we used the conventional propellant L1 whose chemical composition is similar to JA2, but which has an enhanced heat of explosion $Q_{ex} = 5.0$ MJ/kg (equivalent: R 1250; "macaroni"-type grain; diameter 3.3 mm, length 200 mm, web 1.3 mm). The firing results for loading densities between 0.45 and 0.55 g/cm^3, as shown in Fig. 1 (squares), did not depend on the kind of ignition (conventional or by plasma).

A regression curve of the same type as equation (1), but with only two free parameters a and b, whereas p_0 is fixed at the value found before, makes it evident that the kinetic energies obtained with the consolidated JA2 generally exceed those achieved with L1 by 20% to 25% in the interesting region, if compared at equal values of p_{max} (see Fig. 1). Of course, the improved performance of the consolidated JA2 is obtained at the expense of higher amounts of propellant, i.e. increased loading densities.

A reasonable explanation of this finding may be deduced from Fig. 2 comparing two exemplary pressure histories of JA2 and L1 with identical levels of p_{max} = 520 MPa. Obviously, the pressure curve corresponding to JA2 is significantly broader, thus causing an extended period of acceleration and higher muzzle velocity of the projectile.

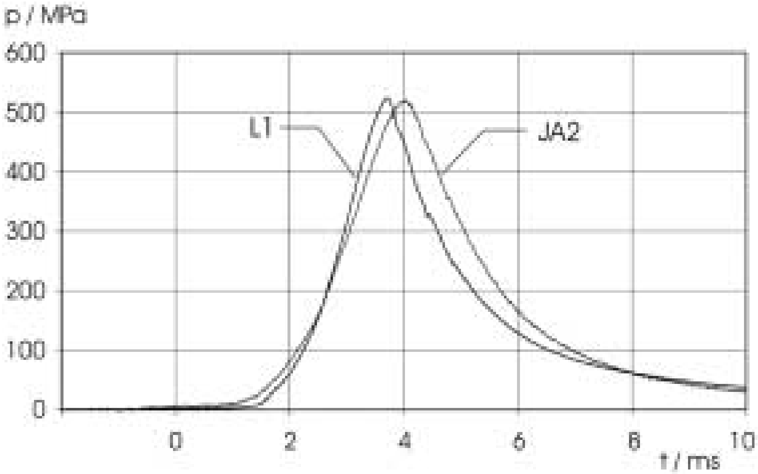

Figure 2: Pressure histories of “standard” JA2 and L1 with equal values of p_{max}.

Before we can increase the loading density further, we must take care that the peak pressure does not exceed the safety threshold.

Modifications of the Projectile

A simple means of lowering the peak pressure p_{max} is to launch a lightweight projectile. With the reference propellant L1 a projectile of mass m_p = 1.55 kg gained so much muzzle velocity v_0 that its kinetic energy E_{kin} remained almost unchanged. Firings with the “standard” charge JA2 in fact resulted in the desired reduction of p_{max}, but E_{kin} and, consequently, the total efficiency ε (the ratio of E_{kin} and the total energy available) diminished severely. These effects are clearly demonstrated in Table 1 (columns 1 and 2). Besides, even worse, the low mass could not avoid strong pressure waves arising at the flank of the pressure curve.

	“Standard” mass	Light mass	“Standard” band	Modified band	
m_p	3.0	1.55	3.0	3.0	kg
Δ	0.79	0.79	0.72	0.73	g/cm^3
p_{max}	750	490	700	550	MPa
v_0	1217	1460	1165	1097	m/s
E_{kin}	2.22	1.65	2.04	1.81	MJ
ε	31.0	23.0	31.0	27.1	%

Table 1: Comparison of “standard” with lightweight and modified projectiles

Another modification of the projectile proved to be more appropriate. The supporting steel cone in front of the polyethylene obturating band was removed in order to reduce the force of extrusion of the projectile into the bore. The results are illustrated in Fig. 3 and listed in Table 1 (columns 3 and 4). Though the maximum pressure p_{max} decreases from 700 to 550 MPa, the total efficiency ε remains sufficiently high at about 27%.

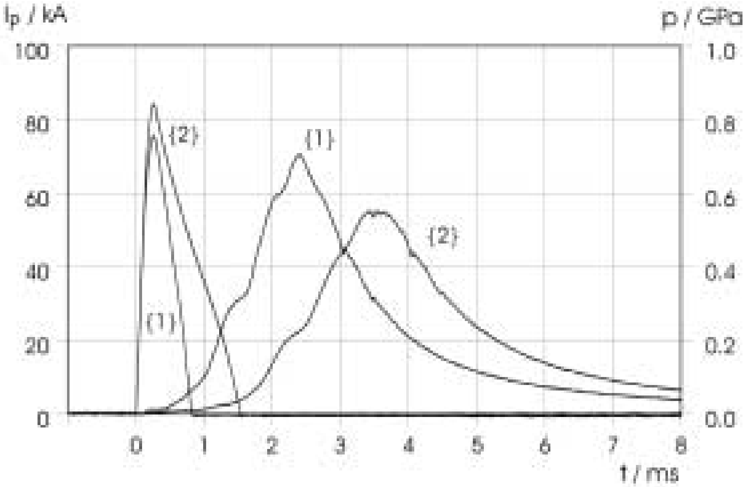

Figure 3: Histories of plasma currents (left) and pressures (right) for “standard” {1} and modified {2} projectile.

Variation of the Propellant Properties

A large part of our activities concerned variations of the propellant properties. Geometrical changes, such as different dimensions of the JA2 grains and 7 or 19 perforations, as well as various thicknesses of the consolidated disks, did not influence the firing performance significantly.

Another step was to study the combustion behaviour of charges made of surface coated JA2 grains treated with different agents, as e.g. polyester. Or the whole surfaces of the disks were coated. However, all these measures did not lead to the desired additional broadening of the pressure curve, but they gave rise to several phenomena which have not been fully understood yet.

One of the main effects with coated grains always was an obvious increase of the ignition delay, as is demonstrated for an extreme delay of about 10 ms in Fig. 4. Here, consolidated disks of the strongly phlegmatized propellant B7T98 (7 perforations; diameter 5.5 mm, length 11.5 mm, web 0.95 mm; Q_{ex} reduced from 4.0 to 3.5 MJ/kg; average density 1.5 g/cm^3) are compared with two examples of the “standard” charge JA2. A similar type of B19T98 yielded good results in our 20-mm ETC gun [2].

The data listed in Table 2 indicate that the firing performance, i.e. E_{kin}, and the total efficiency ε of B7T98 are ranked between the corresponding values of JA2 with the same loading density Δ and JA2 with the same chemical energy E_c.

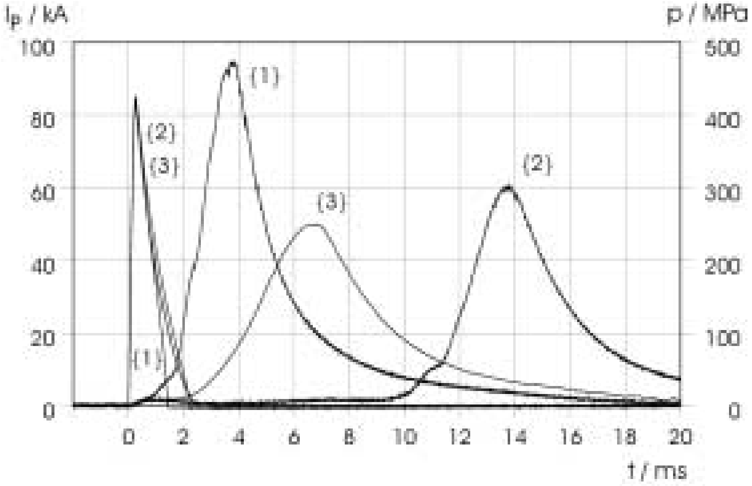

Figure 4: Histories of plasma currents (left) and pressures (right) for "standard" propellant JA2 {1}, {2}, and B7T98 {3}.

	{1} JA2 equal Δ	{2} B7T98 phlegm.	{3} JA2 equal E_c	
Δ	0.65	0.66	0.49	g/cm^3
Q_{ex}	4.7	3.5	4.7	MJ/kg
E_c	5.90	4.46	4.45	MJ
p_{max}	475	300	250	MPa
v_0	1050	905	850	m/s
E_{kin}	1.65	1.23	1.08	MJ
ε	27.8	27.3	24.2	%

Table 2: Comparison of "standard" JA2 with phlegmatized B7T98 charge

Controlled Plasma Ignition

A great advantage of plasma ignition is the possibility of easily adjusting the electrical parameters which influence the initiation of the combustion process. For "standard" JA2 charges with a loading density $\Delta = 0.7$ g/cm^3 Fig. 5 illustrates how the increasing amount of injected plasma energy (namely E_P = 22, 48, and 79 kJ), represented by the current histories $I_P(t)$, makes the ignition delay decrease considerably, while the peak pressure grows only moderately. This effect might be useful for application to the example of B7T98 described in the previous chapter.

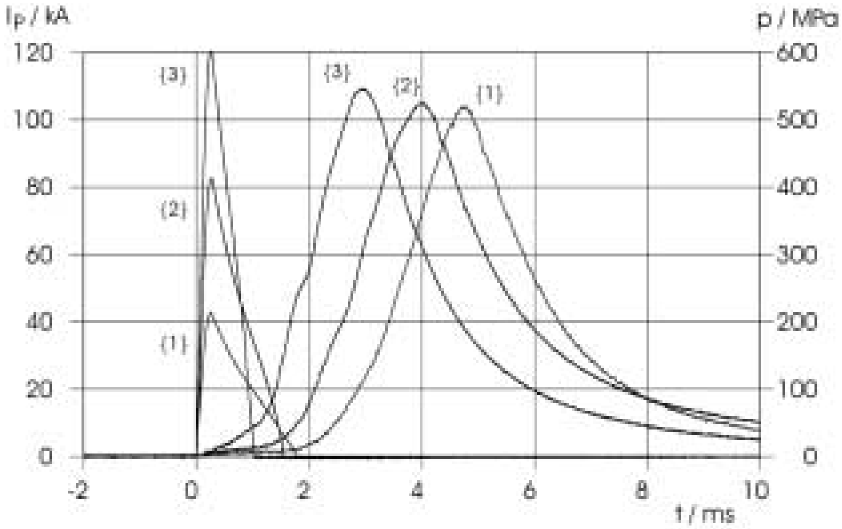

Figure 5: Histories of plasma currents (left) and pressures (right) for three plasma energies (1, 2, and 3 modules).

Our future investigations will concentrate on the optimization of the combustion development by means of locally distributed ignition and consecutively injected plasma energy with precise time delay.

REFERENCES

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2. Kay A., Raupp J., Licht H.-H., Hensel D., Peter H., Zimmermann K., "20-Millimetre ETC Gun Experiments at ISL", *Proceedings of the European Forum on Ballistics of Projectiles*, 193-201, 2000; and: ISL - PU 313/2000