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PLASMA IGNITION AND COMBUSTION

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Electro-thermal-chemical initiation and combustion can increase the performance of guns substantially. This paper reports on investigations of burning phenomena in the low pressure region for JA2, the effects of plasma interaction on ignition and its influence on the burning rate comparing transparent and opaque versions. The high intensity radiation of plasma arcs initiates burning with short time delays in the µs-range and causes high conversion during exposure also in a stable burning. Radiation can penetrate the propellant and fragment the grains at absorbing structures which could be artificial or inherently present. Simplified approaches can explain these effects at least on a qualitative scale including dynamic effects.

1. INTRODUCTION

Electro-thermal-chemical (ETC) initiation and combustion [1–7] could increase the performance of guns as new propellant and high loading densities can be safely ignited and burnt. The propellants ignition occurs by plasma introduced by a jet [1–4] or by an arc from an exploding wire [4–8]. The input of electrical power and energy is measured, but the energy reaching the propellant is unknown. The burning rates have indicated an augmentation of the burning rate increase of the solid propellants [5,8–10]. The improved performance could result from a burning rate increase by the plasma interaction or by grain fragmentation. Recent results analysing extinguished grains indicated that both approaches could be realised. Burning rate formulas like Vieille’s law do not describe sufficiently the effects found [11]. This paper reports plasma effects on ignition and the burning rate for JA2 comparing transparent and opaque versions.

2. SIMPLIFIED APPROACH FOR RADIATION INTERACTION

The explanation of important phenomena of plasma interaction with solid propellants will base on the assumption that the gasification dominates the ignition and burning of solid energetic materials. A detailed outline of this approach is published elsewhere [11–15]. In the following, a radiative energy transfer Q_R is assumed in addition to the energy flux from the flame by conduction Q_0. In the case of an absorption of the total energy flux on the propellant surface which pyrolyses at a temperature T_p, an approximation for the ignition delay time t_{ign} can be found:

$$t_{ign} \approx \frac{\pi\lambda\rho\, c_p \left(T_p - T_0\right)^2}{4\dot{Q}_R^2} \tag{1}$$

For a semi-transparent propellant with a unique absorption coefficient b, a more complicated solution can be obtained [11-15]. If Q_R is constant the following relation for the burning rate r can be derived where the heat conduction from the flame Q_0 is supposed to represent Vieille’s law.

$$r = \frac{A \cdot p^n + \dot{Q}_R}{\rho\left(c_p \cdot \left(T_s - T_0\right)\right)} \tag{2}$$

Eq (2) shows that conductive and radiative heat transfer affect the burning rate in the same way. Eqs (1) and (2) enables to analyse the influence of physical and chemical parameters of solid propellants on ignition delay and linear burning rate. A least squares fit of eq (2) gives the unknown Q_0 ($Q_R = 0$) and T_s when fitting it to r-data measured at various T_o in a closed vessel [15]. For JA2 T_s was found to be close to 675 K [15], and Q_0 increased from 6000 W/cm^2 to 15000 W/cm^2 at pressures from 70 MPa to 175 MPa.

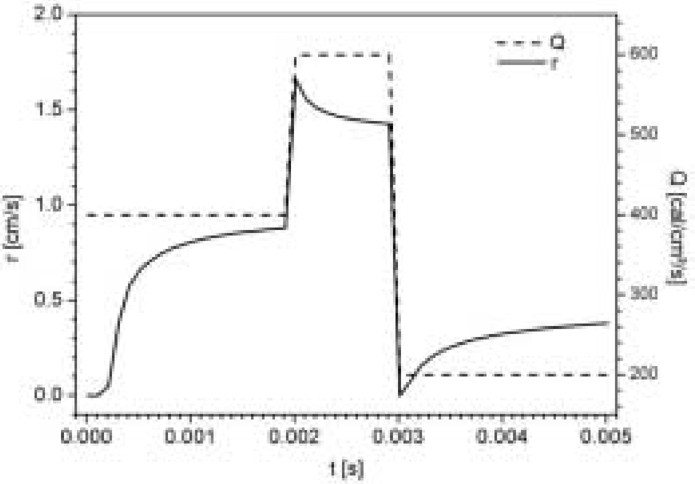

Figure 1: Transient burning rate of a solid propellant (physical data of RDX) on an external heat flux absorbed at the surface.

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Ignition, burning rates and their pressure dependence were calculated also by the method of Zarko and Rychkov (for details see [16–18]). It was applied to the ignition and combustion of nitromethane and a nitramine propellant to energy pulses from external sources [14,16,19]. Fig. 1 and Fig. 2 show the response on heat flux absorbed at the surface (Fig. 1) and in the interior of the propellant (Fig. 2).

The conversion rates of porous and foamed propellants are essentially above those obtained by the linear burning of the compact energetic materials [20]. Using a highly simplified approach of the heat flow equation a three-dimensional calculation can give the conversion of the solid based on overall chemical kinetics and heat of reaction [21]. A detailed description of the application to the plasma interaction with propellants is published elswhere [22].

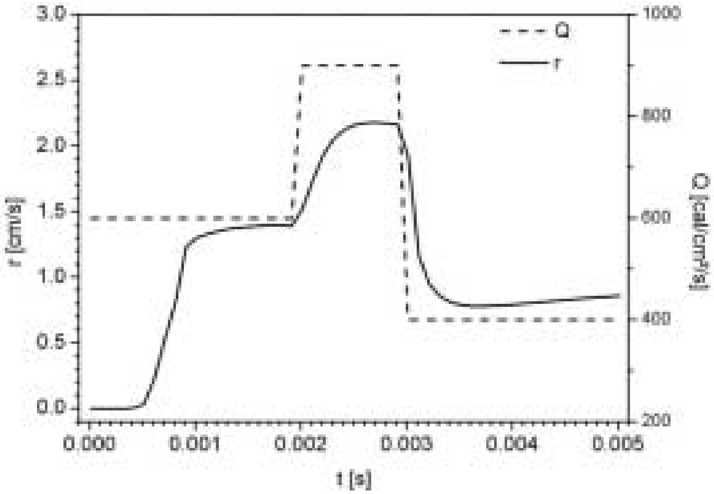

Figure 2: Transient burning rate of a solid propellant (physical data of RDX) on an external heat flux absorbed in depth of the propellant.

3. EXPERIMENTS, RESULTS AND DISCUSSION

Two types of JA2 were used: (1) the standard formulation containing carbon and (2) a transparent version without carbon. The propellants were plates of 3 mm thickness and 20 mm breadth. These plates were shaped to rings and put into a plastic tube (polyamide). The plastic tube fitted into the closed vessel, the distance of the wire to the inner surface of the propellant was 17 mm.

The propellants were investigated in two types of chambers: (1) A closed vessel was used with a volume of 100 ml (most experiments at a loading density of 0.117 g/cm^3, T = 293 K), enabling the registration of the pressure-time behaviour. The wire explosion occurred in the axis of the bomb between electrodes at a distance of 40 mm. (2) The “optical” bomb with windows can withstand pressures up to 13 MPa. It was used for optical and spectroscopic investigations (details see [22,23]). A 100 kJ EVA with maximal voltages of 22 kV enabled ETC ignition and combustion whereas only stored energies up to

10 kJ were used. The resistor was <10 mΩ and the inductivity was 20 µH. The plasma was produced by a wire explosion igniting or pre-treating the propellant. Successive pulses could occur which influence the stabilised burning mode. The voltage was measured at the electrodes and the current by a Rogowsky Coil. The signal data were acquired with sampling rates up to 100 MHz. In the case of propellant plates the burning rates were estimated from the pressure maximum which was related to the thickness of the JA2 and the first derivative of the pressure time curve ignoring the influence of the boundaries of the propellant stripe. Some JA2 plates were pre-treated applying "open" conditions which means that the same plastic tube was prepared with the propellant stripes outside the closed vessel and then the plasma arc initiated.

It was found that the burning rate of black and transparent JA2 are equal if they are not ignited by a plasma or pre-treated by a plasma in an "open" experiment.

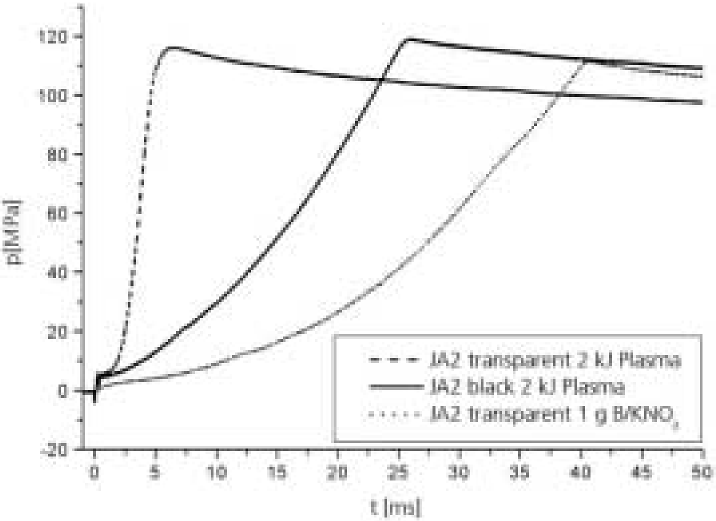

Figure 3: Comparison of plasma ignition of opaque and transparent JA2 and a pyrotechnic ignition.

Fig. 3 shows the pressure time curves of experiments where black JA2, transparent JA2 subjected to a plasma arc of 2 kJ and JA2 initiated by 1 g B/KNO$_3$. The ignition delay indicated by an initial pressure rise is similar for both cases of plasma ignition and faster than that of the conventional ignition. The pressure increase is similar for the black JA2 ignited by plasma and the JA2 ignited by black powder resulting in similar burning rates. The burning rate of the solid material is accordingly higher. The ignition delay decreases with increasing electrical energy fed to the arc. In addition, the pressure increase is steeper if more energy is used (Fig. 4).

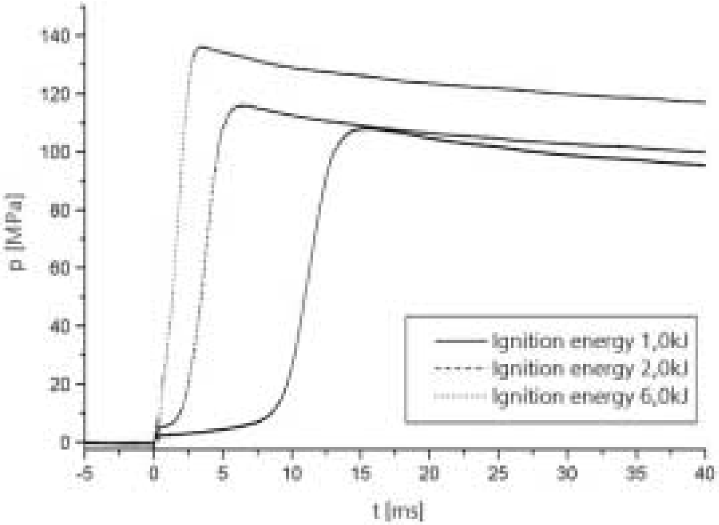

Figure 4: Pressure-time-curves of the ignition of transparent JA2 at various energies.

For the plasma ignition of JA2 it is proposed: (1) *black JA2:* a short ignition time is obtained, only at high radiant fluxes in depth effects could be observed; (2) *transparent JA2:* a short ignition time is obtained, plasma radiation forms a porous structure in the interior of the propellant causing a successive porous combustion characteristics; (3) ignition delay times and burning rate enhancement follow qualitatively the theoretical approaches described above. JA2 was pretreated by a plasma discharge after a wire explosion in open experiments. Black JA2 cannot be pretreated because it ignites and burns under these conditions. The pre-treated JA2 plates shows lens shaped crazes of a diameter of 2 mm orientated parallel to the rolling direction in production of the JA2 plates (see Fig. 5).

Figure 5: Pre-treated transparent JA2 by a plasma arc (0,8 kJ left and 1,5 kJ right).

The following experiments were performed with these pre-treated JA2 plates [11]: (1) Observation of the burning behaviour by a video camera and measurement of the burning rate in the optical bomb described above: The flame front is not linear but penetrates into the crazes forming a broad flame zone still in the solid. The breadth increases whith the pressure. The burning rate is higher than that of non-treated JA2 at 4 MPa and 7 MPa. (2) A detailed analysis of the pressure-time curves obtained by 1 and 2 kJ plasma arc ignition in the closed vessel results in a similar behaviour of the burning rate depending on pressure. There is an increase of the apparent burning rate at 4 MPa and much stronger at

7 MPa above that of black JA2. (3) If ignited by 1 g B/KNO_3 the pre-treated transparent exhibits the same burning behaviour as if ignited untreated by a plasma arc. (4) Experiments with burning interruption indicate that the burning takes place in the lens shaped crazes and voids while the solid keeps its outer shape.

The effect of plasma pulses was investigated by exposing the propellants to one or more arc discharges firstly initiated by the wire explosion. A step by step pressure increase occurs directly related to the electrical pulses. There is only a very short delay between the electrical pulses and the pressure increase. Assuming a reasonable energy transfer (about 10 %) by plasma radiation delay times of less than 100 ns are expected by eq (1) which is in accordance with the experimental results. The regression rate eq (2) of the solid can occur independently of a chemical reaction of the material. In the case of black JA2 which absorbs radiation predominantly on the surface, a result is shown in Fig. 6. There are small time shifts between the pressure increase and the electrical pulses in the order of 100 ns. Conversion rates by the electrical pulses are between 500 mm/s and 2000 mm/s. Assuming a conversion of the propellant material according to eq (2) the energy reaching the propellant surface is estimated to be between 75 kW/cm^2 and 350 kW/cm^2 which corresponds to an efficiency of the transfer of electrical energy of 15 to 20 %. The subsequent burning after the electrical pulses takes place according to the “normal” burning of JA2 with the “normal” burning rates. In cases of higher electrical pulses (> 2 kJ) the transition to the “normal” burning was delayed. The absorption coefficient also of black JA2 does not vanish completely, and, evidently, very strong radiation still penetrates the propellants. Although strongly weakened, it could cause heat input, some crazes and/or fragmentation as in the case of transparent JA2 and influence the conversion.

The burning rate dependence of transparent JA2 on plasma treatment is qualitatively described by the following model [22]: (1) The plasma pulse (as pre-treatment or in the ignition phase) causes crazes and voids in the interior of the propellant which later act as hot spot centres of burning. (2) If the initial pulse does not cause a pressure increase above 2 MPa to 3 MPa then a “normal” linear burning begins including hot spots at the surface. The burning rate does not exceed the burning rate of black JA2. (3) The pressure gradient between the propellant interior and the closed volume drives hot reaction products into the porous structure which cause conversion and burning in the case that the flame quenching distance or the flame stand-off distance is below the size of the pores. (4) This is realised above 4 MPa and the burning occurs within a volume between the surface and a depth where the hot gases can penetrate pores. At 4 MPa to 7 MPa the flame stand-off distance decreased below 1 mm.

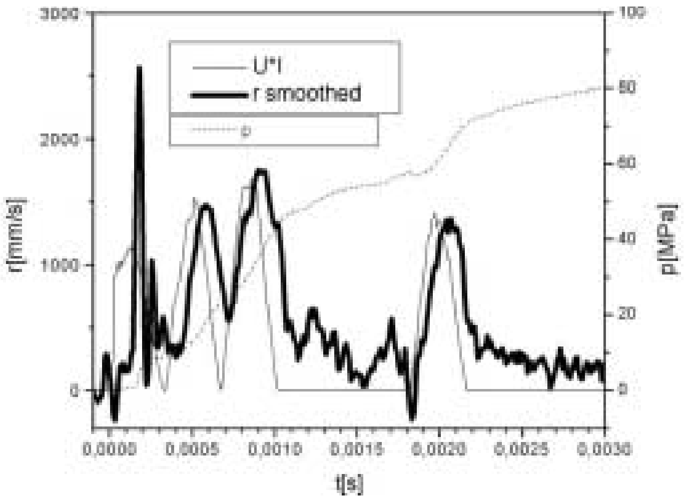

Figure 6: Electrical power, pressure and conversion rates of black JA2.

The hot spot mechanism mentioned above can describe this behaviour on a qualitative scale. The experimental data of Fig. 5 indicate that the enhanced burning occurs immediately if 6 kJ electrical energy are applied. It occurs shortly after the end of the pulse on 2 kJ. On 1 kJ a long delay takes place until reaching a pressure of 4 MPa to 7 MPa by normal burning. Transparent JA2 can be directly pre-treated during the plasma ignition. Its burning characteristics is modified depending on the intensity of the plasma pulse. In generally, in transparent propellants photo absorbing centres or structures could serve to form hot spots under high intensity radiation [11, 22].

4. REFERENCES

1. C. R. Woodley and S. Fuller, “Apparent Enhanced Burn Rates of Solid Propellants Due to Plasmas”, *16th International Symposium on Ballistics,* San Francisco, CA, 23–28 September 1996, pp. 153–162.
2. W. G. Proud. and N. K. Bourne, “The Electrothermal Enhancement of Propellant Burning by Plasma Injection”, *Propellants, Explosives, Pyrotechnics. 22,* 212–217 (1997).
3. A. Bach, N. Eisenreich, M. Neiger, “Charakterisierung eines Plasma-Jets mit optischen und spektroskopischen Methoden”, *22nd Int. Ann. Conf. of ICT,* Karlsruhe, Germany, July 2–5, 1991, pp 98.1–10
4. P. J. Kaste et al., “ETC Plasma-Propellant Interactions”, *29th Int. Annual Conference of ICT,* Karlsruhe, June 30–July 3, 1998, Germany, pp. 125.1–14
5. H. K. Haak, A. M. Voronov, and Th. H. G. G. Weise, “The Interaction of Electrothermally Supplied Energy with Compact Solid Propellants”, *9th EML Symposium,* Edinburgh Scotland, May 13–15, 1998.
6. W. F. Oberle and G. P. Wren, “Radiative and Convective Heat Loss in Electrothermal-Chemical (ETC) Closed Chambers”, *35th JANNAF Combustion Subcommittee Meeting,* Tucson, AZ, December 1998, Vol I, pp. 229–236.
7. D. E. Kooker, “Burning Rate Deduced from ETC Closed-Chamber Experiments: Implications for Temperature Sensitivity of Gun Systems”, *35th JANNAF Combustion Subcommittee Meeting,* Tucson, AZ, December 1998, Vol. II, , pp. 201–217.
8. A. Birk, M. Del Guercio, A. Kinkennon, D. E. Kooker, and P. J. Kaste, “Interrupted-Burning Tests of Plasma-Ignited JA2 and M30 Grains in a Closed Chamber”, *Propellants, Explosives, Pyrotechnics 25,* 133–142 (2000).
9. A. Koleczko, W. Eckl, T. Rohe, “Untersuchungen zur Einkopplung elektrischer Energie in flüssige Energieträger und deren Verbrennungsprodukte”, *27th Int. Ann. Conf. of ICT,* Karlsruhe, Germany, June 25–28, 1996 P-142.
10. A. Voronov, et al. “The Interaction of Electrothermally Supplied Energy with Compact Solid Propellants” *IEEE Trans. on Magn. v 35,* No.1, 224–227 (1999).
11. N. Eisenreich, W. Ehrhard, S. Kelzenberg, A. Koleczko, H. Schmid, “Strahlungsbeeinflussung der Anzündung und Verbrennung von festen Treibstoffen”, *31st Int. Annual Conference of ICT,* Karlsruhe, Germany, June 27–30, 2000, P-139.
12. N.Eisenreich, *“Vergleich theoretischer und experimenteller Untersuchungen über die Anfangstemperaturabhängigkeit von Festtreibstoffen”,* ICT-Bericht 8/77, (1977), Fraunhofer-Institut für Chemische Technologie ICT, Pfinztal, Germany.
13. W. Eckl, S. Kelzenberg, V. Weiser, and N. Eisenreich, “Einfache Modelle der Anzündung von Festreibstoffen”, *29th Int. Ann. Conf. of ICT,* Karlsruhe, June 30–July 3, 1998, Germany, P-154.
14. T. Fischer, G. Langer, N. Eisenreich, “Burning Rate Models of Gun Propellants”, *European Forum on Ballistics of Projectiles,* EFBP’2000, Saint-Louis, France, April 11–14, 2000, 117–127.
15. N. Eisenreich, W. Eckl, Th. Fischer, V. Weiser, St. Kelzenberg, G. Langer, A. Baier, “Burning Phenomena of the Gun Propellant JA2”, *Propellants, Explosives, Pyrotechnics 25,* 143–148 (2000).
16. V. E. Zarko, L. K. Gusachenko, and A. D. Rychkov, “Simulation of Combustion of Melting Energetic Materials” *Defence Science Journal 46* No. 5, pp. 425–433, (1996).
17. L. K. Gusachenko, V. E. Zarko, and A. D. Rychkov, “Modeling of Gasification of Evaporated Energetic Materials under Irradiation” *INTAS Workshop,* Milan, July (1996).
18. S. Kelzenberg, N. Eisenreich, W. Eckl, V. Weiser, “Modelling Nitromethane Combustion”, *Propellants, Explosives, Pyrotechnics. 24,* 189–194 (1999).
19. N. Kubota, T. J. Ohlemiller, L. H. Caveny and M. Summerfield, *15th Symposium (International) on Combustion,* Tokyo 1974, pp. 529.
20. T. S. Fischer , W. Koppenhöfer, G. Langer, M. Weindel, “Modellierung von Abbrandphänomenen bei porösen Ladungen”, *30th Int. Ann. Conf. of ICT,* Karlsruhe, Germany, June 29–July 2, 1999 P-98.
21. G. Langer, N. Eisenreich, “Hot Spots in Energetic Materials”, *Propellants, Explosives, Pyrotechnics, 24,* 113–118 (1999).
22. A. Koleczko, W. Ehrhardt, H. Schmid, St. Kelzenberg, N. Eisenreich, “Effects of Plasma on Ignition and Combustion of Energetic materials”, *Propellants, Explosives, Pyrotechnics,* to be published.
23. W. Eckl, V. Weiser, G. Langer, and N. Eisenreich, “Burning Behaviour of Nitramine Model Formulations”, *Propellants, Explosives, Pyrotechnics 22,* 148–151 (1997).