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SUMMARY

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STUDII ȘI CERCETĂRI REFERITOARE LA DEZVOLTAREA METODELOR DE INIȚIERE PENTRU AMESTECURILE PROPULSIVE
STUDIES AND RESEARCH ON THE DEVELOPTMENT OF IGNITION METHODS FOR PROPELLANT MIXTURES

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Chapter 1 The current state of knowledge on propellant mixtures and the analysis of classical types of propellants

Chapter 1 presents the theoretical basis for propellant mixtures, with an emphasis on the classification and analysis of classical propellants. Starting from the definition of energetic materials and explosive transformation processes (deflagration, combustion, detonation), the two major categories were detailed: gun propellants and rocket propellants.

Propellants were described according to their composition (single, double and triple base), geometry (flakes, spherical, cylindrical, with channels, rosette type) and combustion type (progressive, neutral, regressive), as well as their main properties. The study of the combustion process was analyzed based on the burning rate law expressed by three empirical relations.

Finally, the factors influencing the actual combustion behavior, sensitivity and risks associated with these mixtures were highlighted.

1.1 Introduction

Energetic materials are defined as substances or mixtures of substances, in metastable states, which can undergo an explosive transformation following the action of an external impulse [1].

Explosive transformation is a self-propagating, rapid physicochemical process with the release of heat and gases, which can take three forms: deflagration (intensely exothermic decomposition reactions and oxidation-reduction reactions [1]), combustion (thermal impulse ignition, with propagation velocities from a few millimeters to a few meters per second [2]) and detonation (fast and exothermic physicochemical process, with reactions that propagate supersonically through the energetic material).

1.2 Classification of energetic materials

In order to divide energetic materials into categories, the explosive transformation was taken into account, followed by the destination and composition of each type of explosive as shown in Figure 1.2. [1]

Gun propellants are mixtures of one or more explosives with various plasticizers and additives, carefully designed and processed to burn easily, without detonating under normal conditions of use.

Depending on the number of energetic bases, gun propellants can be classified into single base propellants (NC-nitrocellulose), double-base propellants (NC with NG-nitroglycerin) and triple-base propellants (NQ-nitroguanidine, NC and NG) [3].



Figure 1. 1 *Classification of energetic materials in terms of explosive transformation*

Rocket propellants are explosives designed to detonate uniformly to generate propulsive energy. They are divided into liquid propellants (monopropellants – a single compound, bipropellants – oxidizer and fuel [3]) and solid propellants, where all the elements are already in the combustion chamber, and combustion control depends on the shape of the combustion surface [3].

1.3 Combustion analysis of propellants

Combustion generates gaseous products at high temperatures. Depending on the combustion chamber, the production of these gases can also lead to high pressures. Depending on the substances included in the composition, combustion can also produce solid residues [4].

The propellant combustion process comprises three phases [5]: priming (initiation by external stimulus), ignition (propagation of the reaction on the particle surface, influenced by pressure, shape and the primer used) and combustion itself (propagation of the reaction in the thickness of the propellant elements, in a direction normal to the surface of the elements).

One of the most important characteristics of a propellant is its burning rate. The firing phenomenon is also influenced by the force and covolume of the propellant, the geometry and dimensions of the propellant elements [4].

The burning rate refers to the velocity of the regression of the burning surface within the thickness of the propellant element, along the normal direction to the respective surface.

To describe the burning rate law, in the specialized literature, there are 3 main empirical relations.

The first relation is written as:

$$u = Ap^{\nu} \tag{1.1}$$

where A and ν depend on the propellant nature and the combustion conditions

The second relation specific to the burning rate was given by Professor S.P. Vucalov and can be written as:

$$u = ap + b \tag{1.2}$$

This relation is expressed by the two coefficients a and b which depend on the propellant nature.

In parallel, a group of French researchers proposed a third relation specific to the burning rate law as follows:

$$u = \theta p \tag{1.3}$$

where θ- coefficient of proportionality.

As can be seen, this last relation is a particular case of the first relation for $\nu = 1$.

According to the classification made by Krier (1975) and Eisenreich (2002), the burning rate of a propellant element is influenced by its geometry and composition, as well as by properties such as porosity, density and thermal interaction [6].

The analysis of the energetic materials sensitivities to different stimuli highlights the relevance of the tests for assessing the risk of accidental initiation. Based on these results, rigorous measures for the protection and safe handling of energetic materials will be implemented.

Chapter 2 Research on propellant ignition methods used in propellant systems

The chapter highlights the role of ignition mechanisms, the variety of existing solutions and their impact on the performance and safety of propulsive systems. The main ignition methods are classified – by impact, friction, thermal stimulus, electrical, gas and laser – each with its own advantages and limitations.

Theoretical foundations, mathematical models and test procedures are presented, as well as the factors influencing these processes. Examples include the analysis of heat losses in the closed vesse and the study of parameters specific to laser ignition, where the emphasis is on the use of Nd:YAG lasers and laser diodes.

Finally, a synthesis of the specialized studies and the conclusions drawn from them is made.

2.1 Introduction

Traditional energetic materials that initiate the propellant ignition are black powder, boron-potassium nitrate ($BKNO_3$), a mixture of nitrocellulose and black powder (benite), or an igniter, the composition of which is 98% nitrocellulose.

These energetic materials initiate ignition by combining convective heat transfer from hot gases and thermal conduction from hot particles deposited on the surface of the propellant grains.

2.2 Classification of propellant ignition methods

2.2.1 Conventional propellant ignition

Closed vessels are the equipment used to analyze the propellant combustion and the gas formation process at constant volume. In the closed vessel, the variation of gas pressure related to time p=f(t) is obtained.

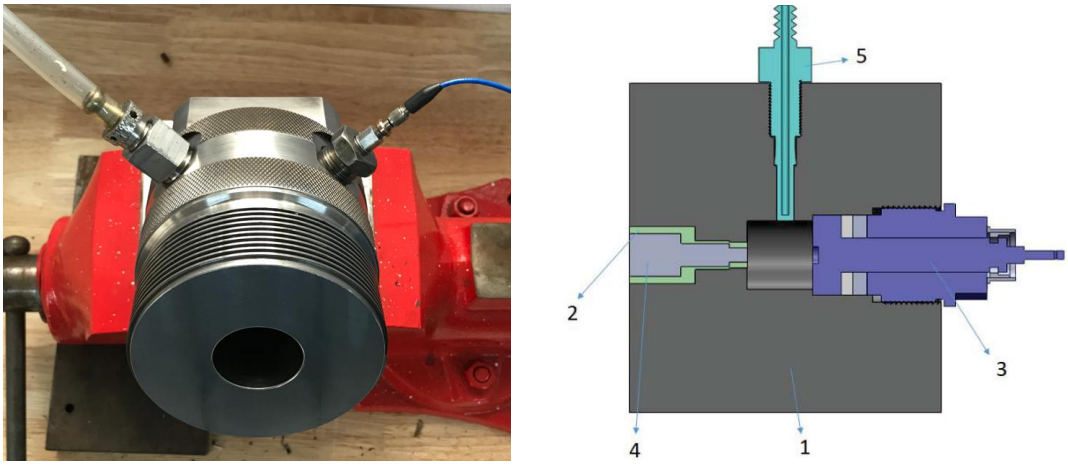


Figure 2. 1 *The main components of the closed vessel, with a volume of 40 cm^3, represented in solidworks* [7]

The influence of heat losses in closed vessel

During experimental tests in the closed vessel, since conditions are not ideal, part of the thermal energy released by the propellant combustion is lost by heating the vessel walls. This leads to a decrease in maximum pressures compared to the situation where there would be no losses [5].

Heat losses are quantified using Newton's formula [5]:

$$dQ = \alpha_t S_b (T_g - T_p) dt \tag{2.3}$$

where : dQ represents the amount of heat transferred to the closed vessel walls, α_t- the heat transfer coefficient, S_b- the inner surface of the closed vessel, T_g- the temperature of the propellant gases and T_p- the temperature of the vessel walls.

2.2.2 Friction ignition

When two surfaces slide past each other, the energy dissipated by friction becomes the source of heat at the interface between the two surfaces. The intensity of friction is influenced by the load acting on the surface, the sliding velocity, and the roughness of the material [8].

Friction sensitivity is one of the most important factors to test in the evaluation of new explosive compositions and is determined using the BAM apparatus, figure 2.2. The tested material is placed between two porcelain plates, on which a load is applied

by means of an alternating electric motor [9]. When the system is operated, the behavior of the tested material is observed and classified as “reactive” or “non-reactive”.

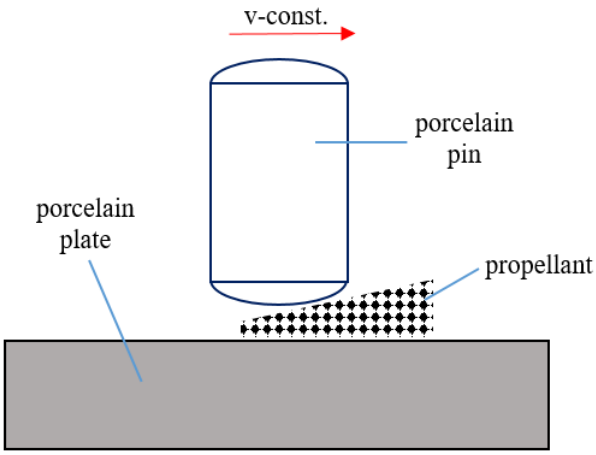


Figure 2. 2 *Position of the porcelain plate before operating the BAM device*

2.2.3 Impact ignition

Impact ignition of explosives remains a hot topic in the field of pyrotechnics. To increase the safety of munitions, explosives must be sufficiently insensitive to unpredictable stimuli. However, if the sensitivity is reduced, the applied pressure must be increased to ensure safe ignition of the main charge. For this reason, shock initiation models are used to assess both the risks and reliability of explosives [10].

Impact sensitivity is the property of explosives to detonate upon impact and is a parameter that characterizes their safety during handling and transportation. It is expressed in Joules (J), practically representing the minimum impact energy at which the explosive sample explodes [11].

The test to determine the impact sensitivity of explosives is performed using a hammer-type device (Kast hammer) following the norms of STANAG 4489 [12]. The method consists of dropping a hammer of specified mass, from a fixed height, onto the explosive sample being tested and determining the minimum impact energy at which at least one reaction is obtained, out of six attempts [12].

2.2.4 Direct laser ignition

Studies in the field have analyzed the behavior of energetic materials at different impulses and the variety of their chemical structures, including propellants, pyrotechnic elements, and primary or secondary explosives. To choose an appropriate laser system, process aspects and the main radiation parameters are analyzed, such as pulse width, beam profile and repetition frequency, respectively its power.

The choice of laser for initiating energetic materials depends on the application requirements, the most commonly used being **Nd:YAG lasers** and **laser diodes**. The Nd:YAG laser is preferred due to its efficiency, low cost and versatility (1064 nm, pulsed or continuous mode), and laser diodes operate based on p-n semiconductor

junctions. The research focused on experiments using various types of lasers (UV, visible, near-IR and IR lasers). Within the doctoral research, experimental tests and performance evaluations were focused on Nd:YAG laser ignition.

2.2.5 Laser-driven flyer ignition

The technique of initiating explosives by laser-driven flyer ignition is an indirect method of igniting energetic materials using a laser. The principle consists of a pulsed laser beam, given by an Nd-YAG laser system, which is focused through the transparent substrate (glass) to which an aluminum foil has been glued (figure 2.6). The irradiated area heats up rapidly and is discharged as plasma. This causes additional heating of the underlying layer of aluminum foil and imparts sufficient mechanical force to tear off a section of the aluminum foil. The formed flyer travels through the air at high velocities, up to 1.6 km/s.

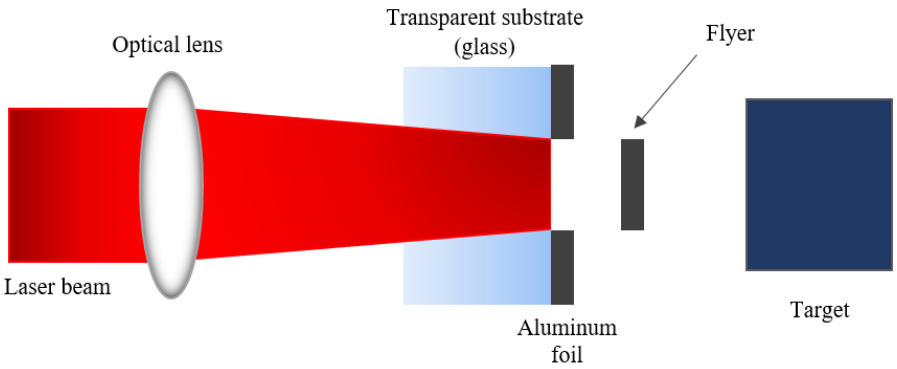


Figure 2. 3 *Schematic of explosives initiation by laser-driven flyer ignition*

The flyer velocity can be described in a double exponential form as follows:

$$u(t) = A_1\left(1 - e^{-B_1(t-t_0)}\right) + A_2\left(1 - e^{-B_2(t-t_0)}\right) \quad (2.13)$$

where: A_1, A_2, B_1, B_2 *and* t_0 are the fitting parameters and B_1, B_2 represent the high acceleration in the initial phase, respectively the low acceleration in the subsequent phases.

2.2.6 Propellant ignition using a gas

Previous studies, such as that carried out by Leciejewski [13], investigated the single base propellant combustion through comparative tests in a closed vessel, comparing classical (electric), plasma and gas ignition. The results show that gas and plasma initiation accelerate ignition, and in the case of plasma, dynamic effects related to the rapid movement of the plasma flow occur [13].

Ballistic properties depend significantly on ignition conditions, with burning rates varying by up to 20%. For fine propellants, the amount of black powder used influences the ignition mode, with a higher dose being required to create conditions similar to simultaneous ignition [13]. Gas and plasma ignition methods, along with

sample positioning in the closed vessel, bring the ignition process as close to ideal as possible [13].

2.3 Conclusions

The analysis of propellant ignition methods highlights the transition from classical techniques (electric, friction) to modern solutions (laser, gas). Traditional methods, although used, have safety and integration limits, while modern ignition offers precision, speed and reduced risk of accidental triggering. Laser ignition is distinguished by rigorous control of parameters and innovative techniques, such as laser-driven flyer ignition. In this context, the research direction chosen in the thesis is justified by the superior potential of the laser method, the next chapter being dedicated to experimental research on the propellants behavior under different stimuli.

Chapter 3 Experimental research on the propellant mixtures combustion in the closed vessel and the reaction of propellant mixtures to thermal stimuli, impact and dynamic stresses

Chapter 3 presents experimental research on the propellants characterization by classical methods. Tests in the closed vessel highlighted the influence of thickness and density on burning time: NBL lamellar powders, with thinner elements, reacted faster, while tubular and 7-channel propellants showed the slowest pressure increase.

Sensitivity determinations complemented these results, showing that double-based propellants (especially MBG) are more sensitive to impact and friction, while single-based propellants prove to be much safer, even being classified as insensitive to friction. From a thermal point of view, most propellants showed acceptable stability, with decomposition temperatures around 180 °C.

Another series of tests, carried out on 7-channel propellants through the Hopkinson bar system, confirmed their low sensitivity, the reactions observed being only of a mechanical and thermal nature, without ignition.

Overall, the chapter provides a detailed characterization of propellants by standardized methods, constituting a basis for comparison for modern ignition techniques.

3.1 Introduction

In the previous chapter, various methods of initiating energetic materials were presented. An essential step in the process of evaluating the performance, reliability and safety of pyrotechnic and propulsion systems is the characterization of the behavior of energetic materials to different stimuli. These stimuli can come from mechanical or electrostatic sources. Therefore, it is important to know the sensitivities of explosive

compounds. The significant values that need to be determined are related to the sensitivity to impact, friction, electrostatic and thermal [14].

3.2 Experimental pressure determination tests. Pressure measurement using the piezoelectric system

The study of the energetic materials combustion plays an important role in the firing phenomenon. Given that the process is complex, in order to determine the combustion laws of compositions as well as the formation of gases, experimental tests are carried out. The device with which experimental tests can be carried out is called the closed vessel.

Experimental tests were carried out using seven types of propellants, at different loading densities (100 kg/m^3, 150 kg/m^3 and 200 kg/m^3) divided into categories as follows:

- Simple base propellants
  - 7 channels (multichannel cylindrical elements)
  - tubular (cylindrical elements with a single channel)
- Double-base propellants
  - NBL-11, NBL-42, NBL-62 (lamellar elements)
  - MBG (graphitized, lamellar propellant)
  - Nitrochemie (small cylindrical elements)

The combustion of each explosive composition gave us results in the form of the p=f(t) profile. Figure 3.5 displays in a comparative manner the graph with the evolution of pressures over time for each type of propellant used, at a loading density of 100 kg/m^3.

The results show that the propellants burning time increase with the thickness of the propellant elements and decrease with the charge density. The 7-channel and tubular propellants burn the slowest, reaching maximum pressure after 22.67 ms and 32.98 ms, respectively, while the other types reach this value in less than 6 ms.

MBG propellant has the fastest pressure rise, reaching its maximum value in less than 3 ms due to its fine particles and uniform distribution that favors accelerated combustion.

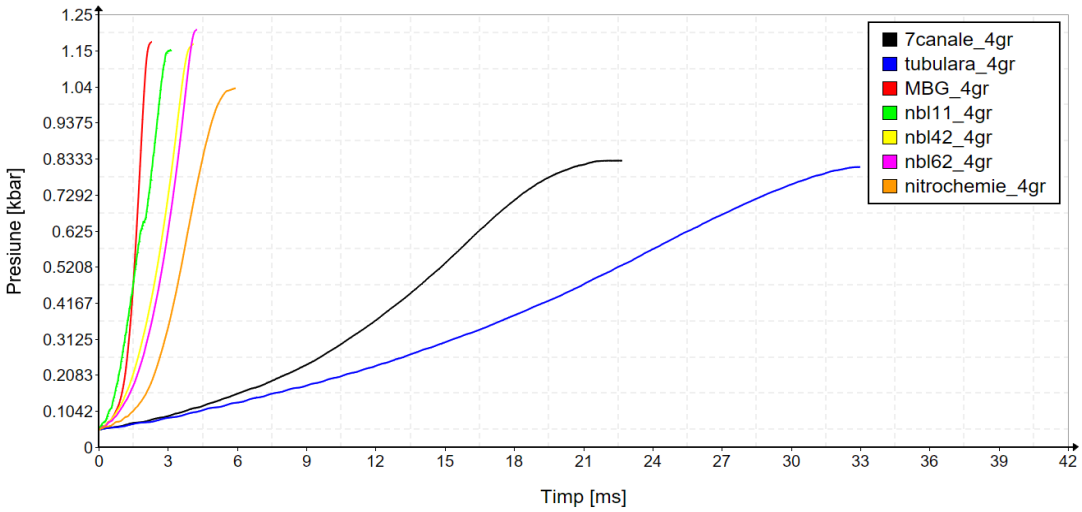


Figure 3. 1 *Comparative graph of specific pressure profiles of different types of propellants at a loading density of 100 kg/m^3*

3.3 Experimental tests on impact sensitivity of propellant mixtures (KAST Hammer)

The sensitivity of explosives to impact was evaluated by the Kast drop hammer test [12], starting from an energy of 10 J and gradually reducing to the absence of reaction. The results showed that the tested samples present sensitivities ranging from 3 to 20 J, with significant differences between the types of propellants: MBG propellant proved to be the most sensitive, confirming the behavior also observed in the closed vessel tests, while single base propellants (tubular and 7-channel) presented the lowest sensitivity, requiring higher minimum ignition energies. The correlation of the results suggests that the ignition mechanisms by mechanical shock are comparable to those of combustion propagation, and the sensitivity to impact is closely related to the electrical one, both being influenced by the structure and morphology of the propellants.

3.4 Experimental tests on the thermal sensitivity of propellant mixtures

For the most comprehensive analysis of explosive devices from a safety and performance perspective, it is necessary to know the thermal characteristics of explosive materials.

The purpose of performing these types of tests is to establish the thermal characterization of an explosive material using differential thermal analysis.

Differential thermal analysis (DTA) records the temperature difference between a substance and a thermally inert reference material. The propellants used in the experiments were described in the previous section.

Differential thermal analysis (DTA) demonstrated that the thermal behavior of the propellants used is directly dependent on their chemical composition.

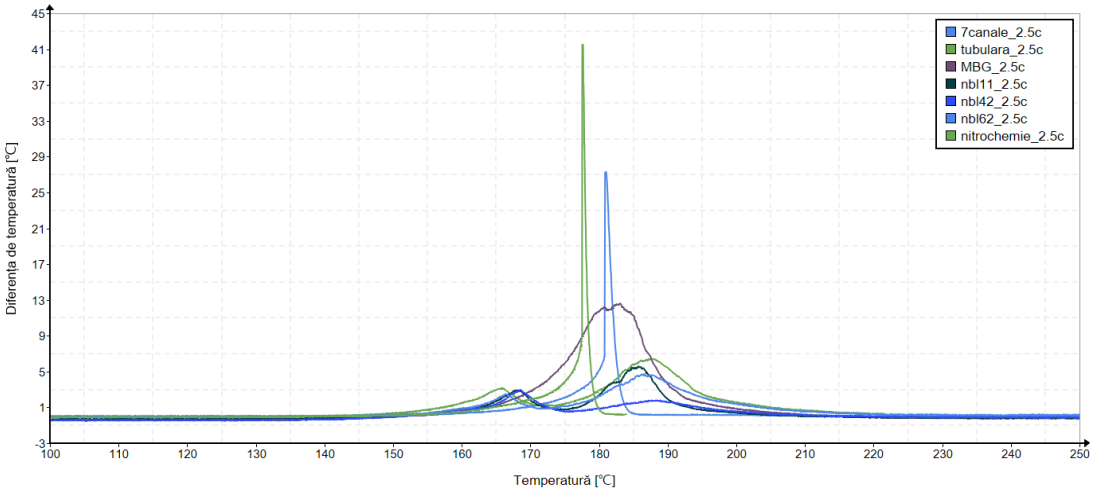


Figure 3. 2 *DTA thermogram corresponding to the temperature increase rate* $(2.5℃/\boldsymbol{min})$

The characterization of the formulations by DTA analysis showed that the behavior to the thermal stimulus is strictly dependent on their chemical composition. The simple base propellants (tubular and 7 channels) present the largest temperature difference compared to the reference material. As can be seen, the propellants used present an acceptable thermal sensitivity, which is found around 180 ℃, regardless of the temperature increase rate (2.5 *or* 5 $℃/min$).

3.5 Experimental tests on the friction sensitivity of propellant mixtures

The most well-known method for testing and determining the sensitivity of an energetic material to friction is the BAM Friction Sensitivity Tester according to STANAG 4487 [9]. One of the most common causes of accidental explosions is due to friction sensitivity.

To obtain relevant results in which over 50% of the cases are favorable, a number of 25-30 tests are performed for each sample at different pressing forces. A volume of 10 mm^3 propellant is weighed, which will be placed on the porcelain plate in the form of a relay of 10 mm length, arranged perpendicular to the roughness marks of the porcelain plate [9]. The propellant compositions were of lamellar, granular and disc type, the same propellants used and presented in the previous sections.

The results obtained from the tests can be of the form: no reaction, decomposition, initiation, pops and explosion depending on the sensitivity of each tested propellant.

The results showed that most samples are sensitive to friction loads between 168 and 252 N, except for the simple base propellants (tubular and 7-channel), which did not react even at the maximum value of 360 N. The tests confirm the observed trend also for impact sensitivity: impact-sensitive compositions exhibit the same behavior under friction. The MBG propellant proved to be the most sensitive, while the lamellar propellants (NBL-11, NBL-42, NBL-62) showed close thresholds, initiating at around

216 N, and the Nitrochemie propellant was the least sensitive, requiring over 252 N for ignition. Initiation was manifested by popping noises or visible decomposition traces on the porcelain plate.

3.6 Experimental studies on the propellants response induced by dynamic shock loads with the Hopkinson bar system

The Hopkinson bar system is used to study the behavior of materials under dynamic loading by transmitting and reflecting compression waves in a cylindrical specimen. The reflected wave and the transmitted wave are proportional to the values of strain and stress in the specimen [15].

In tests performed on low-sensitivity propellants with 7 channels and cylindrical shape, at velocities of 5–20 m/s, temperature variations caused by internal friction and particle cracking were observed. However, these stresses did not lead to the initiation of the propellant reaction, demonstrating the stability of the tested compositions under dynamic conditions.

3.7 Discussion and results

The results in Table 3.9 show clear differences between single and double base propellants in terms of impact, friction and thermal behavior (DTA) sensitivity. The MBG propellant proved to be the most sensitive, initiating at only 3 J in the impact tests and maintaining the same trend in friction, where the ignition threshold was below 216 N. In contrast, the tubular and 7-channel propellants were the safest, not reacting even at the maximum load of 360 N, and the Nitrochemie propellant showed the lowest sensitivity to friction, requiring over 252 N for ignition.

Thermal tests indicated acceptable stability for most propellants, with decomposition temperatures around 180 °C, with the largest differences observed for single-base propellants. Overall, the results confirm the correlation between mechanical and thermal sensitivity, highlighting the decisive influence of particle structure and morphology on propellant behavior.

Table 3. 1 *Sensitivity test results*

	7 channels	**tubular**	**MBG**	**NBL-11**	**NBL-42**	**NBL-62**	**nitrochemie**
Impact sensitivity [J]	6	8	3	5	6	6	6
Friction sensitivity [N]	insensitive	insensitive	168	216	216	216	252
Thermal sensitivity [℃]	180.9	187.9	182.8	185.6	168.4	186.1	177.5

Chapter 4 Experimental research on the integration of the laser ignition system for propellant mixtures into the closed vessel

Chapter 4 presents research on the integration of a laser system into the closed vessel. An optical system was developed that allowed both direct ignition of the energetic charge and indirect ignition using a primer. The results showed that the indirect method favors rapid and uniform propagation of combustion, reducing delay times and confirming the feasibility of using the laser as an ignition means.

Another experimental direction focused on transmitting the laser beam through Plexiglas tubes, demonstrating the possibility of ignition even with curved tubes or with sharp ends, which concentrate the laser energy. Tests on simple-base propellants revealed a faster increase in pressure with increasing charge mass, with performance being improved by using tubes.

Comparison with classical methods showed that electrical ignition remains superior, but laser ignition offers advantages such as precision and parameter control, despite limitations related to optical losses and the need to optimize configurations.

4.1 Introduction

The motivation for research into laser ignition of energetic materials is derived from the need for adaptable, fast-acting, and highly reliable devices that can meet the specific criteria of some types of insensitive munitions.

Laser ignition of propellants has followed two main directions. First, measuring the sensitivity of propellant grains to the energy transmitted by the laser beam (effects of the physical and chemical characteristics of the material) and second, developing and testing a practical laser ignition system.

4.2 Design of the laser ignition system and its integration into the closed vessel

4.2.2 Direct laser ignition

The ignition of energetic materials was experimentally achieved by integrating a laser system into the closed vessel, connected to a data acquisition system (transducer, conditioner, oscilloscope and Picoscope software). Comparatively, ignition tests with a laser promoter were performed with and without using a primer (black powder). Figure 4.4 b highlights the new vessel cap subassembly, equipped with a visor and a glass lens, which allowed the passage of the laser beam, adjustment of focus and maintenance of alignment in the ignition direction.



(a) (b)

Figure 4. 1 *(a) Closed vessel, (b) Laser system integrated into the closed vessel* [16]

Three types of propellants were used in the tests: PR-1 (lamellar propellant NBL-11), PR-2 (lamellar propellant NBL-42) and PR-3 (small cylindrical propellants).

From the graph in Figure 4.8, it can be distinguished that in the case of indirect laser ignition, the charge ignition was faster and the maximum pressure reached exceeded the pressure value obtained normally.

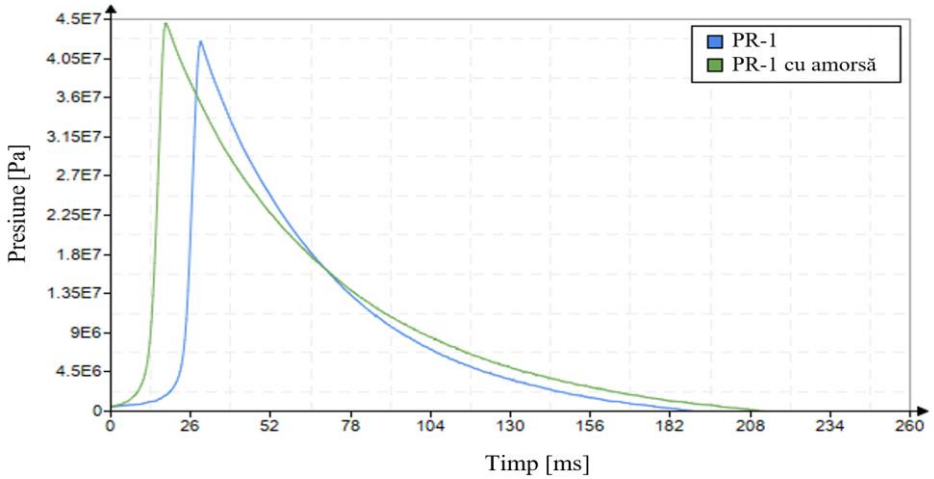


Figure 4. 2 *Comparative analysis of PR-1 composition between direct and indirect ignition* ***[16]***

4.2.3 Laser ignition through plexiglass tubes

In order to transmit the laser beam to the energetic material, plexiglass tubes were used, a cheap solution that was easy to integrate into the closed vessel. The tests used a laser with a wavelength of 520 nm, a power of 3 W, operating in continuous mode, and black powder was used as primer, given the insensitivity of military explosives to laser stimuli. The tested propellants were single based, cylindrical, with a single perforation. The experiments began with single-point ignition and evolved towards the establishment of multi-point systems. In addition, due to the flexibility of the plexiglass tubes, an attempt was made to initiate the composition by bending them (figure 4.15), and the tests demonstrated the ignition success.



(a) (b)

Experimental setup during the tests

Figure 4. 3 *Experimental configurations with the plexiglass tube arranged: horizontally (a) and (b) curved*

Laser ignition tests through the plexiglass tube were performed on 4 g and 6 g propellant charges, respectively, in which black powder was used as a primer, representing 10% of the charge.

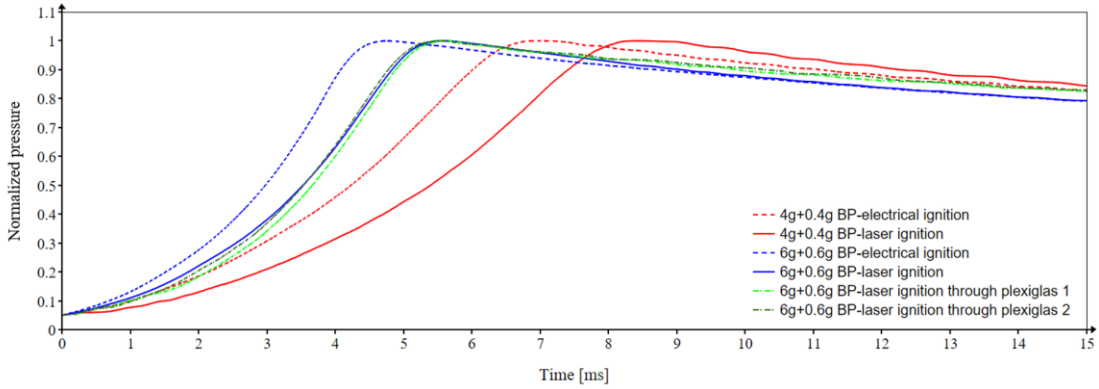


Figure 4. 4 *Pressure evolution at different charge densities and different ignition methods: classical electrical ignition (dotted lines), laser ignition (solid lines) and laser ignition through plexiglass tubes (marker lines)*

In figure 4.18 it is observed that the pressure rate increase depends mainly on the charge mass, with electrical ignition being the fastest, followed by laser ignition, including through plexiglass tubes. At high loads, all methods produce rapid reactions, and at low loads the differences become more evident, confirming that electrical ignition has an advantage at low masses.

4.3 Conclusions

In the closed vessel configuration, laser ignition – both direct and through plexiglass tubes – has proven effective, especially with the use of a black powder primer, which ensures rapid and uniform ignition. Plexiglass tubes allow for beam deflection and focusing, improving performance, but the electrical method remains

superior. Future research aims to use optical fibers for simultaneous ignition at multiple points and increasing combustion uniformity.

Chapter 5 Experimental Research on Laser Explosive Ignition

Chapter 5 presents experimental research on the explosives ignition with a pulsed Nd:YAG laser (1064 nm, spot ~3 mm), analyzing two methods: laser-driven flyer ignition and direct laser ignition. For foils of different thicknesses (40 μm, 2×40 μm, 3×40 μm, 100 μm) the ignition thresholds, impact velocities and delay times were determined, noting that thinner foils provide faster ignitions at lower energies. The direct ignition process takes place in three stages (plasma formation, ignition and combustion) and is influenced by the beam parameters, but has longer delays.

5.1 Introduction

The energetic materials ignition by means of laser systems appeared in the early 1960s. Ruby, CO_2 and Nd:YAG lasers were used, with pulsed operation at wavelengths between 0.266 μm and 1.06 μm [17].

The use of laser-based ignition systems represents a significant advance over conventional systems, particularly due to their reduced susceptibility to electromagnetic interference. Also, the advent of new high-power laser diodes allows the development of new lightweight and autonomous ignition systems using optical fibers [18].

5.2 Experimental methods

Two approaches have been used to ignite explosives. In the first approach, the laser beam is directly incident on the target, initiating a self-sustained combustion process that, if the conditions are right, can transition to deflagration and then detonation.

The second approach is to use the energy created by the vaporization of the metal foil to propel the flyer towards the explosive charge. The wave induced in the explosive by the flyer impact will cause the shock wave to transition into a reactive detonation front [19].

5.2.1 Laser-driven flyer ignition

The study of ballistic impact on energetic materials led to the use of flyer-type projectiles that proved to be an effective method for analyzing the dynamic behavior of pyrotechnic compositions to shock-type stimuli [20].

In figure 5.13 - detail a, it can be seen how the laser pulse disperses a solid part of the surface of the aluminum foil, and the formed flyer hits the tested sample, igniting its upper surface.

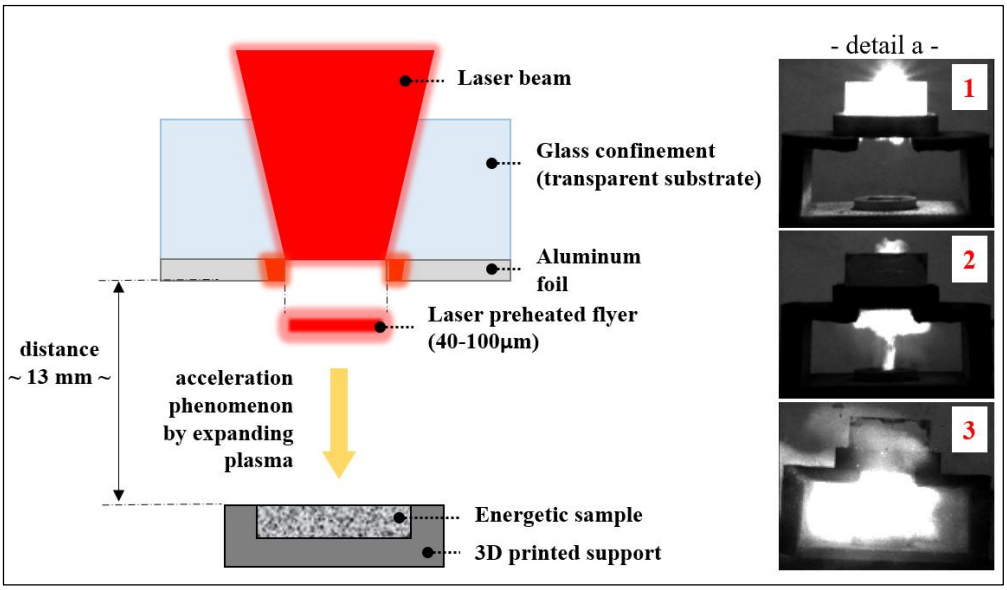


Figure 5. 1 *Laser-driven flyer forming process (1 - plasma formation; 2 - impact of the energetic sample by the flyer; 3 – sample ignition)* ***[21]***

Testing configuration 1 flyer of 40µm

Experimental tests were performed using laser energies between 100 mJ and 2800 mJ.

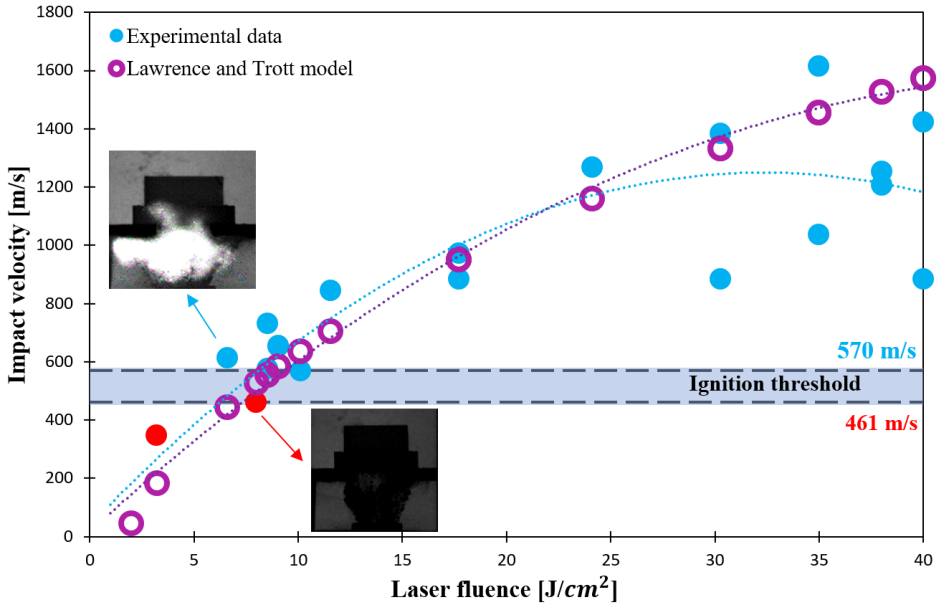


Figure 5. 2 *Comparative analysis of the experimental model with the Lawrence and Trott model in the analysis of the impact velocity for a single 40µm foil* ***[21]***

The graph in figure 5.14 shows a good correspondence between the Lawrence–Trott model and the experimental data, with deviations at high fluences (> 40 J/cm²) [22] due to optical failure of the glass and energy losses in the plasma [21]. Additional variations are due to the foil quality and the precision of its bonding to the glass.

Testing configuration 2-3 flyers of 40µm

The scheme in figure 5.13 was modified by introducing 2–3 40 µm metal foils, to evaluate the influence on the flyer formation and propellant ignition. The results show that the minimum velocity required for ignition is 569 m/s when using two metal foils and 423 m/s for three metal foils, and the fluence/energy range is very narrow: below 2801 mJ the flyer is not formed or the velocity required for ignition is not reached [21].

Testing configuration 1 flyer of 100µm

Experimental results show that for a 100 µm metal foil propelled by the laser, the minimum threshold of impact velocity required for ignition is approximately 315 m/s, which is lower than in the cases with 2 or 3 metal foils. This is because a thicker aluminum foil requires higher laser energy, but the resulting metal foil is propelled at a lower velocity [21].

The graph in figure 5.18 shows that the maximum impact velocity is obtained with the 40 µm aluminum foil, and increasing the thickness or foils number leads to a decrease in velocity and the need for higher laser energy to form the flyer. The minimum energy thresholds are 130 mJ for one 40 µm foil, 90 mJ for one 100 µm foil, 260 mJ for two 40 µm foils and 210 mJ for three 40 µm foils.

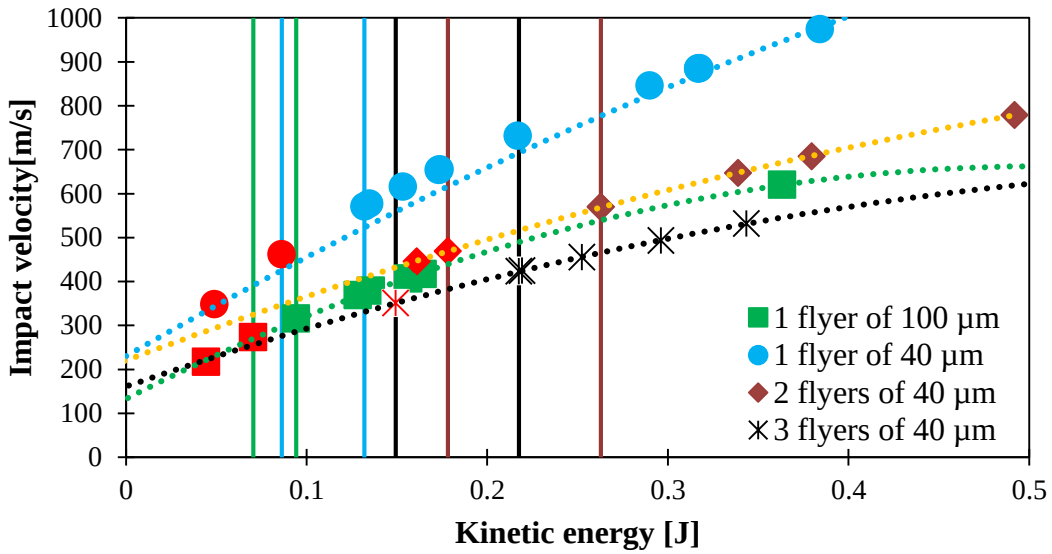


Figure 5. 3 *Evolution of impact velocities obtained in the case of explosives ignition for laser-driven configurations (red markers signify the ignition failure)* ***[21]***

5.2.2 Direct laser ignition

The experimental methodology is shown in figure 5.21. In this case, the laser beam is transmitted directly onto the energetic material, initiating a self-sustained combustion process that can progress from deflagration to detonation (DDT).

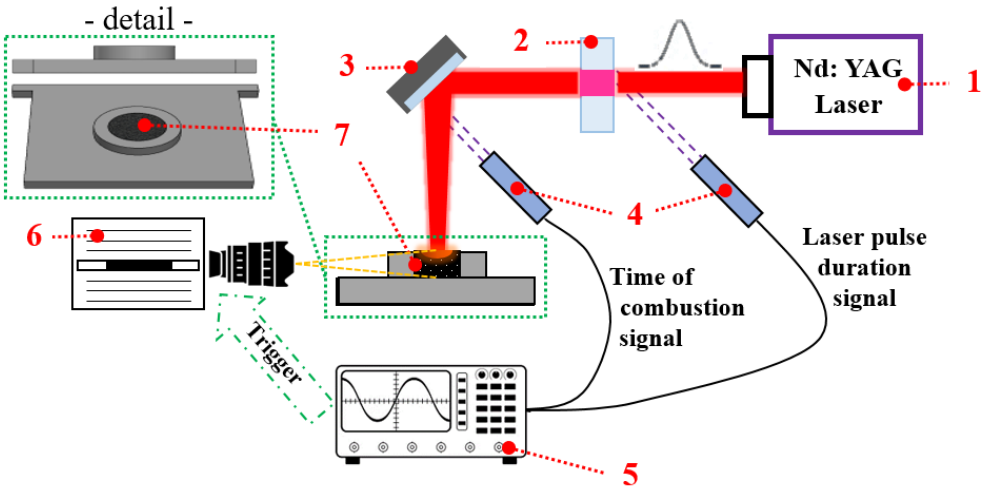


Figure 5. 4 Experimental setup for direct laser ignition

(1 – laser system; 2 – optical lens; 3 - mirror; 4 - photodiodes; 5 - oscilloscope; 6 – high-speed camera; 7 – testing platform and pyrotechnic sample) ***[21]***

In the direct laser ignition tests, samples of approximately 200 mg of propellant were used, placed in a cylindrical support. The direct laser ignition process occurred through the "hot spot" ignition mechanism [23], at fluences between 0.71 and 15.095 J/cm². Above fluence values of 0.815 J/cm², ignition occurred in 100% of cases, and the minimum energy required was 57 mJ, lower than in the case of laser-driven flyer ignition, due to the lack of intermediate material [21].

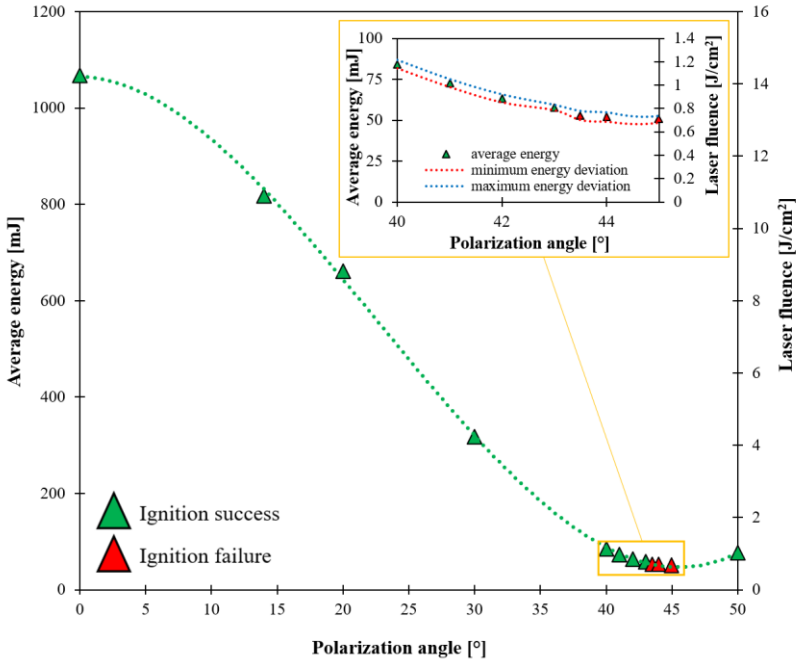


Figure 5. 5 *Laser energy evolution vs fluence and polarization angle* ***[21]***

5.3 Conclusions and discussions

The chapter presents a comparison between direct laser ignition and laser-driven flyer ignition. The use of aluminum foils provides faster and more efficient ignition, but requires higher laser energies, and delay times increase proportionally with their thickness. Direct laser ignition has a significantly lower energy threshold, but leads to slower ignition, with well-defined stages. The results broadly confirm the Lawrence–Trott model and show that the beam parameters, together with the geometry and environmental conditions of the samples, decisively influence the ignition mechanism. Overall, foil propulsion demonstrates a high potential for fast and controlled ignition, contributing to the development of advanced and safe technologies for pyrotechnic systems.

Chapter 6 Numerical modeling of laser-driven flyer ignition method

Chapter 6 presented the numerical modeling of laser-driven flyer ignition method with LS-DYNA, using a 2D axisymmetric model and specific constitutive laws for each material. The laser beam was equated by an ablation pressure applied to the aluminum foil. The simulations showed the formation and rupture of 40 μm and 100 μm flyers at energies of 2826 mJ, confirming the agreement with the experimental results. The model proved to be valid, but it requires the parameters adjustment and the transition to 3D simulations for a more faithful description of the phenomenon.

6.1 Introduction

The study of very high velocity impacts is an essential field with direct implications for current research and applications. To reproduce and analyze these phenomena in the laboratory, it is necessary to accelerate various types of projectiles to velocities of kilometers per second.

A promising method in this regard is the generation of projectiles by laser irradiation. This method has the advantage of obtaining projectiles with varied geometries while maintaining a high rate of fire.

6.2 Experimental configuration

The experimental setup (figure 6.1) used a laser with a laser spot diameter of 3 mm. The pulse energy was measured with a joulemeter and the temporal intensity profile with a photodiode, data that allowed the estimation of the ablation pressure by the numerical code ESTHER.

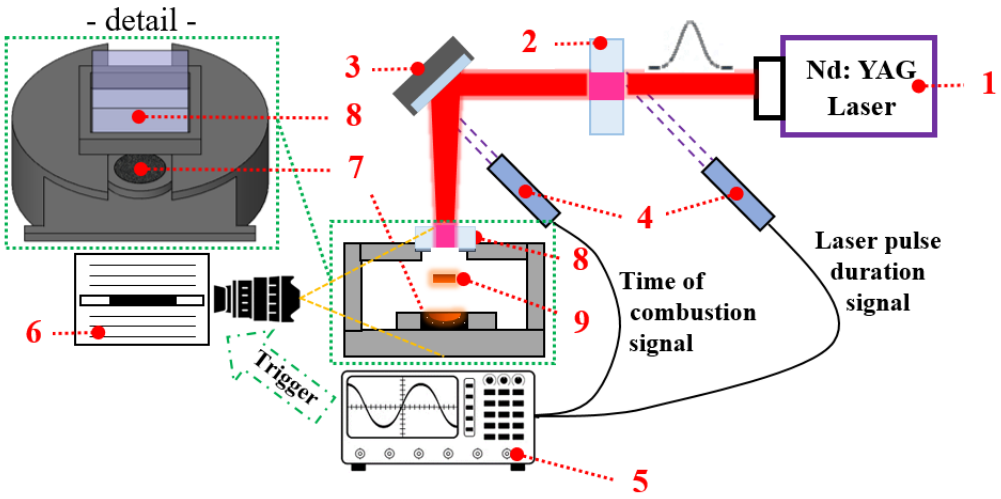


Figure 6. 1 Experimental setup for laser-driven flyer ignition

(1 – laser system; 2 – optical lens; 3 - mirror; 4 - photodiodes; 5 - oscilloscope; 6 – high-speed camera; 7 – testing platform and pyrotechnic sample; 8 – glass and aluminum foil; 9 – flyer)

6.3 Numerical modeling

To analyze the behavior of the metal foil and the assembly subjected to laser radiation, the finite element method (LS-DYNA) was used. The configuration of the LS-DYNA model, together with the finite element discretization and the pressure distribution are illustrated in figure 6.3. In the simulations, the laser energy of 2826 mJ was equated by an ablation pressure applied to the aluminum foil, which led to the formation and propulsion of the flyer.

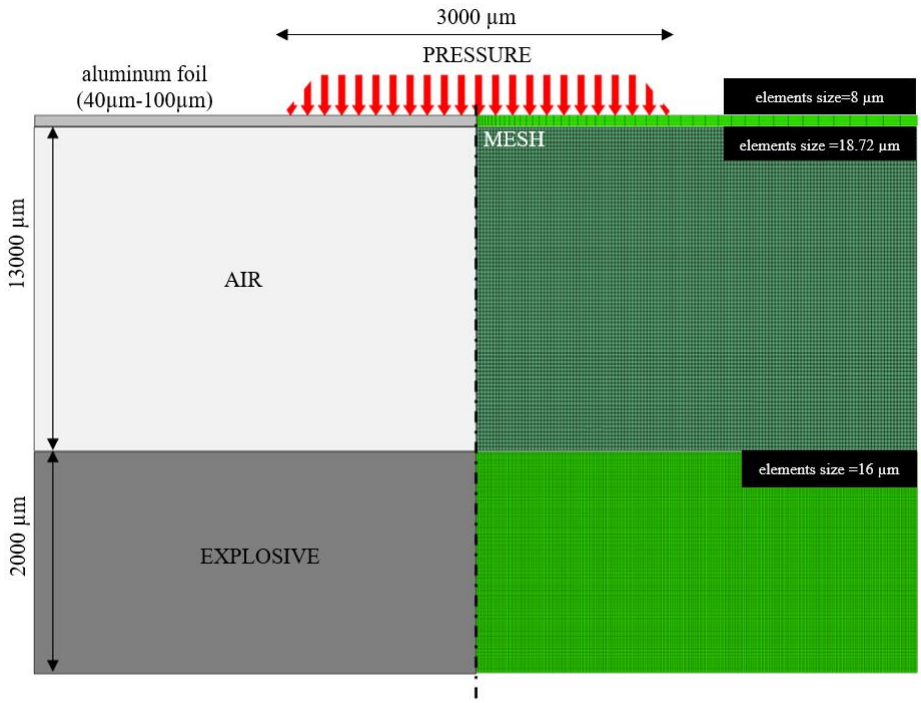


***Figure 6. 2** LS-DYNA model: finite element discretization and pressure distribution*

The ablation pressure was described by the relation:

$$P(x,t) = \left[1 - \frac{1}{\pi} arctan\left(-\frac{x}{R}\right)^{12}\right] \cdot A(t) \quad (6.1)$$

where A represents the time function of the pressure amplitude, x represents the position along the aluminum foil that determines the spatial pressure distribution and R represents the laser spot radius.

unde A reprezintă funcția temporală amplitudinii presiunii, x reprezintă poziția de-a lungul foliei de aluminiu care determină distribuția spațială a presiunii iar R reprezintă raza spotului laser.

6.4 Results

In this section, the formation and propulsion of an aluminum foil by ablation is analyzed, following the dynamics of the flyer over a distance of 13 mm. Figure 6.9 illustrates the evolution of a 40 μm flyer, from the moment of detachment from the foil (t=0.11989 μs) to the impact with the explosive layer (t=9.3999 μs).

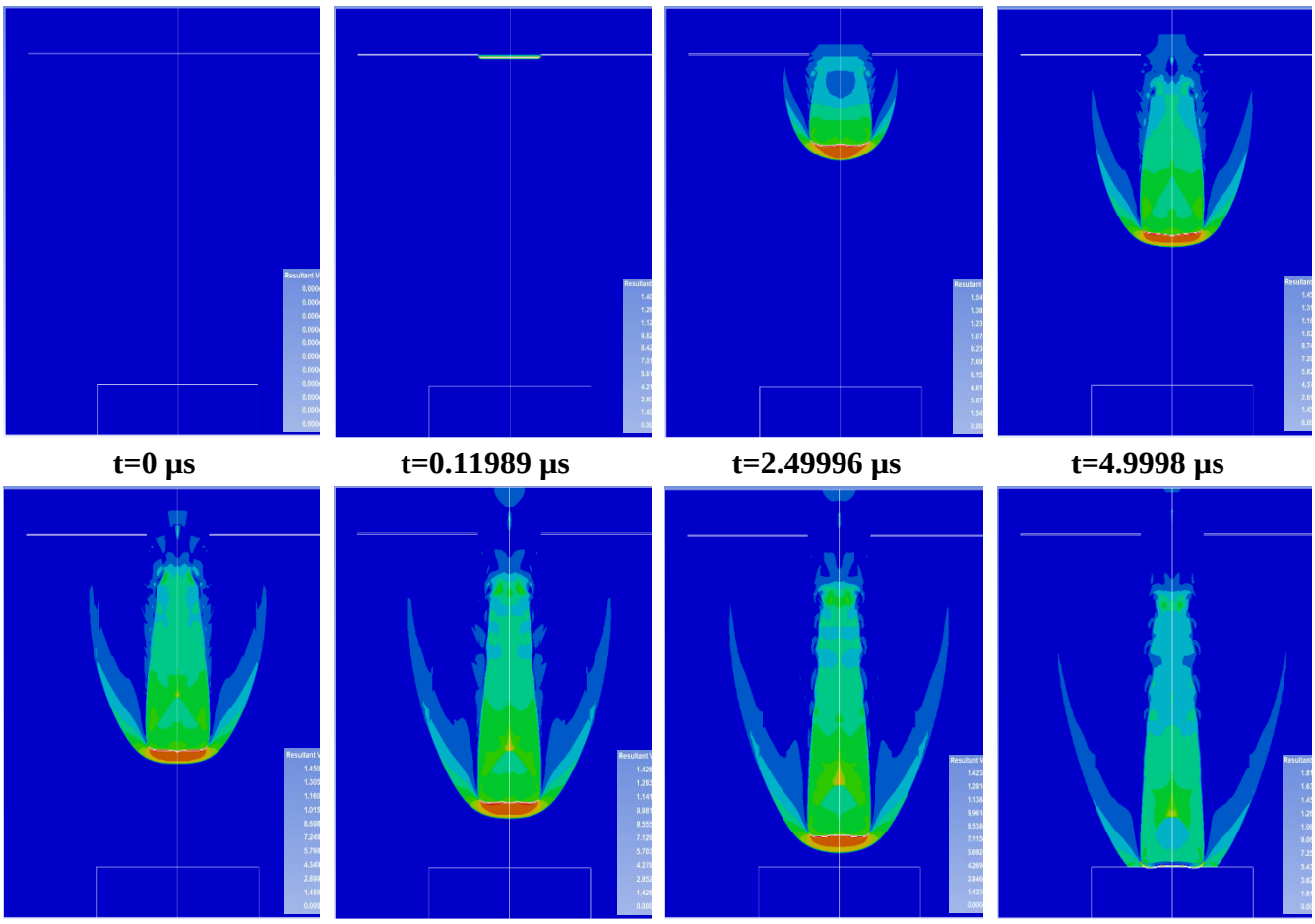


Figure 6. 3 *Numerical results regarding the formation of the 40 μm flyer and its trajectory until the impact with the explosive*

Figure 6.11 shows the velocities evolution of the 40 μm and, respectively, 100 μm aluminum foils over time, for a laser energy of 2826 mJ. The foil rupture is clearly

observed in the area of the maximum values of the two profiles: at t = 0.12 μs for the 40 μm foil, respectively t = 0.42 μs for the 100 μm foil. This is due to the reduced mass and lower mechanical strength of the thin foil, which ruptures faster, influencing the mode of impulse transmission and the foil dynamics along the trajectory. The velocity of the 40 μm foil is approximately twice that of the 100 μm foil, the same trend being confirmed in the experimental case.

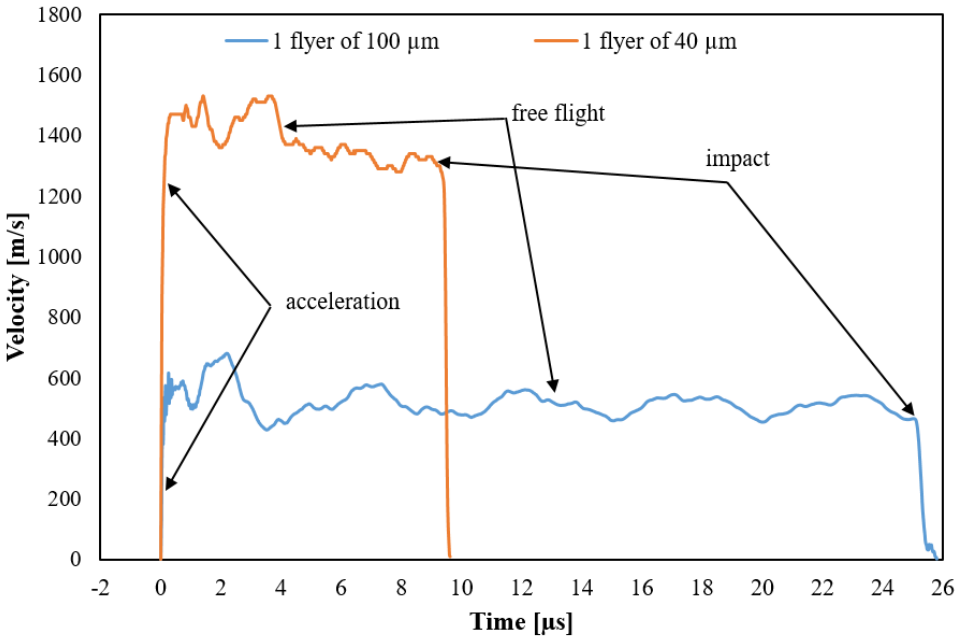


Figure 6. 4 *Element velocity at the center of the flyer for each of the two configurations (40 μm and 100 μm metal foil) versus time. The velocities reach zero at the impact moment with the sample*

6.5 Conclusions and discussions

This chapter analyzes the propulsion process of aluminum foils by laser irradiation, focusing on the modeling and evaluation of the mechanical behavior of 40 μm and 100 μm foils. The 2D axial-symmetric numerical simulations correctly reproduced the formation and dynamics of the flyer, the results being consistent with the experimental data regarding the velocity, momentum and distance traveled. However, the small differences observed suggest the need for parameter adjustment, through more advanced constitutive models, optimization of the discretization and the transition to 3D simulations. Future directions aim to integrate explosive materials into the model to reproduce the real detonation and obtain a more precise validation of the propulsion phenomenon.

Conclusions

In the doctoral thesis "Studies and research on the development of ignition methods for propellant mixtures", fundamental and applied aspects regarding the behavior of propellant mixtures and explosives during classical ignition and laser ignition were investigated, both from an experimental perspective and through

numerical modeling. The study targeted the essential stages of the combustion and detonation process, the sensitivity parameters to mechanical and thermal stimuli, as well as the integration of modern laser ignition technologies, including the laser-driven flyer ignition. The results obtained confirm the correlations between the structure and morphology of the propellants, the physicochemical parameters and the combustion process dynamics, while also highlighting the potential of laser ignition methods in increasing safety and control over energetic reactions.

Obtained results

The doctoral thesis presents a complete approach to propellant mixtures and their ignition, starting from theoretical foundations to experimental research and numerical modeling. The types of energetic propellants, their classification by composition, geometry and burning mode, as well as the laws of burning rate and the factors influencing the real behavior, sensitivity and associated risks are detailed.

Ignition methods of powders and explosives, from impact, friction, and thermal or electrical stimulus, to gas or laser ignition, were analyzed. For each method, theoretical principles, mathematical models, influencing parameters, and test procedures are discussed, emphasizing the importance of safety and performance of propellant systems.

Experimental studies using classical methods, such as closed vessel tests and determination of sensitivity to impact, friction and temperature, have allowed the comparative characterization of single-base and double-base propellants.

The results showed notable differences in sensitivity and combustion behavior, confirming, for example, that MBG propellants are the most sensitive, while simple base propellants prove to be much more stable. Dynamic tests with the Hopkinson system highlighted the mechanical response of the propellants without initiating the reaction.

The integration of the laser beam as an ignition method demonstrated the advantages of this technology, both through direct and indirect ignition, as well as by laser beam transmission using plexiglass tubes. Experiments highlighted a fast and uniform ignition, with more precise process control, but also limitations due to optical losses.

Extensive research with the pulsed Nd:YAG laser has focused on both direct ignition of energetic compositions and propulsion of metallic foils. Energy and velocity thresholds have been established for various foil configurations, with thinner foils being observed to allow higher velocities but requiring better energy control. In comparison, direct ignition requires lower energies but with higher laser spot accuracy, while laser-driven flyer ignition provides more efficient and faster ignitions.

Finally, numerical modeling of the laser-driven flyer ignition process using the finite element method confirmed the good correlation with the experimental results, while also highlighting the limits of the 2D approach and the need to perform 3D simulations for a more accurate description of the phenomenon.

Original contributions

The original contributions of this thesis are found in both the experimental and numerical modeling parts, aiming at the propellants characterization, the development and testing of modern laser ignition methods and their validation by comparison with classical methods and theoretical models. The main contributions brought by this research are presented below:

1. Complete experimental characterization of single and double base propellants through standardized tests (closed vessel, impact, friction and thermal sensitivity) [2,3];
2. Testing 7 channels propellants through the Split Hopkinson Bar system (SPHB), demonstrating the lack of ignition under dynamic shocks (5–20 m/s) and characterizing their mechanical behavior under dynamic loads [4];
3. Integration and testing of a laser ignition system into the closed vessel, both through direct and indirect ignition (using a primer), as well as the transmission of the laser beam through plexiglass tubes [5];
4. Demonstration of the possibility of transmitting and deflecting the laser beam by bending plexiglass tubes and analysis of the performances obtained;
5. Comparison of electrical ignition, direct laser ignition, and laser ignition through plexiglass tubes, highlighting the advantages and limitations of each method;
6. Study of explosives laser ignition through two approaches: laser-driven flyer ignition and direct laser ignition, by establishing ignition thresholds, with specific values of energy, ignition time and associated impact velocities [6,7];
7. Validation of experimental data by reporting to analytical models and highlighting ignition mechanisms (impact vs. thermal effect) [7];
8. Development of a 2D axially-symmetric numerical model in LS-DYNA for the laser-driven flyer ignition process, by equating the laser energy with an ablation pressure and validating the results obtained against experimental data.

List of original publications

1. **Răzvan Mircioagă**, Liviu Matache, Adrian Rotariu, Marius Cîrmaci, Pamfil Șomoiag, Laviniu Haller, Alexandru Rancea, "Burning law determination using numerical simulation of propellants burning in the closed vessel," IOP Conf.Series: Materials Science and Engineering, vol. 916, 2020.

2. **Răzvan Mircioagă**, Adrian Rotariu, Tudor Prisecaru, Florin Dîrloman, Bogdan Pulpea, Ionuț Predescu, Experimental study regarding burning process specific to different types of propellants by means of closed vessel tests, UPB Scientific Bulletin, Series D:Mechanical Engineering, Vol.85, Iss.2, 2023, ISSN 1454-2358

3. Florin Dîrloman, Traian Rotariu, Tudor Țigănescu, **Răzvan Mircioagă**, Considerations Regarding Modern Solid Rocket Propellants, Journal of Military

Technology, 17-24, Vol.6, Iss.1, 2023, ISSN 2601-6613
4. **Răzvan Mircioagă**, Tudor Prisecaru, Adrian Rotariu, Julien Le Clanche, Baptiste Reynier, Michel Arrigoni, " Experimental study on the dynamic behavior of low-sensitivity propellant grains with the split hopkinson pressure bar," in Proceedings of International Scientific Conference “Defense Technologies”, Schumen, 2024.
5. **Răzvan Mircioagă**, Adrian Rotariu, Bogdan Pulpea, Florin Dîrloman, Study of the gun powders ignition by laser beam in closed vessels, New Trends in Research of Energetic Materials, 2024, ISBN 978-80-7560-507-8
6. Baptiste Reynier, **Răzvan Mircioagă**, Julien Le Clanche, Lorenzo Taddei, Jean-Marc Chevalier, David Hébert, Michel Arrigoni, "High-velocity laser-driven flyer impact on paraffin gel," International Journal of Impact Engineering, vol. 202, 2025.
7. **Răzvan-Marian Mircioagă**, Baptiste Reynier, Tudor Prisecaru, Adrian-Nicolae Rotariu, Florin-Marian Dîrloman, Liviu-Cristian Matache, Laviniu Haller, " Advancing ignition techniques for energetic materials: A comparative study of direct laser ignition and laser-driven flyer methods", Defence Technology Journal, Advance online publication, 2025, https://doi.org/10.1016/j.dt.2025.09.005.

Perspectives for further developments

The results obtained in the doctoral thesis "Studies and research on the developtment of ignition methods for propellant mixtures" provide a solid basis for further research. The main directions of future development are:

- **Extension of experimental studies**: testing triple base, composite and eco-friendly propellants; analysis of military and civilian explosives (RDX, HMX, PETN); correlation of sensitivity with microstructural parameters;
- **Optimizing test setups** by using optical fibers to split the laser beam and achieve simultaneous and uniform multi-point ignition. Use of other types of lasers (CO_2);
- **Improving numerical modeling** by using 3D numerical simulations with the integration of the detonation reaction, for a more rigorous validation of the models and a detailed understanding of the propulsion phenomena;
- **Investigating the applicability of laser ignition systems** in real industrial and military use conditions, with a focus on safety, reliability and costs;
- **Creation of combined ignition methods** (laser-electric or laser-chemical) to increase the flexibility and reliability of ignition systems .

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