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IMPROVING THE INTERIOR BALLISTICS PROCESS BY USING CHARGES OF PROPELLANT GRAINS OBTAINED THROUGH ADDITIVE MANUFACTURING

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Abstract: *In this paper is presented a method for solving the interior ballistics model when is used a charge of propellant grains composed of different energetic materials and obtained through additive manufacturing. Starting from the premise that the burning of these types of propellant grains is carried out in several phases, at different moments of time and using a more vivacious propellants for secondary phases, leads to a good approximation of the ideal ballistic cycle which represents a rapid increase of the pressure up to the maximum value and maintaining it until the entire propellant charge is completely burned.*

Keywords: interior ballistic, grain design, additive manufacturing, ideal ballistic cycle

1. Introduction

Over time, there has been a consistent interest among armed forces in increasing the effective range of artillery weapons in order to destroy enemy forces from distance. This desire has presented a challenge for researchers, who aim to achieve this goal without developing new weapon systems [1]. The typical way to measure the effectiveness of a gun system is by analyzing the changes in pressure and projectile velocity as the projectile travels through the gun barrel [2]. So, one possible solution is to modernize the ammunition, particularly the propellant charges/high-energy solid propellants. By improving the propellant charges, the kinetic energy of the projectile in the gun barrel can be increased, resulting in a higher muzzle velocity, while adhering to the restrictions placed on the maximum and operating pressure in the gun barrel. This improvement can be accomplished by introducing new energetic materials or using different geometries of the propellant grains.

In the literature [2], [3] it is highlighted that the burning of the propellants and formation of the gases play an important role in the firing phenomenon. When solid propellant is ignited within the combustion chamber, it undergoes a combustion process that transforms chemical energy into thermal energy, generating hot combustion products and rapidly pressurizing the loading chamber [2]. At the start, the projectile faces considerable resistance to motion, leading to high chamber pressures before it moves. As the projectile moves through the gun barrel, the combustion products expand and propel it at a high velocity, causing the volume behind the projectile to increase and the pressure to decrease. However, the burning rate of the solid propellant is influenced by pressure, resulting in a more vivacious burning due to the high pressure generated before the

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projectile motion. These opposing effects compete with each other, leading to a rapid increase in pressure until it reaches its maximum value. Afterward, the pressure gradually decreases.
The ideal interior ballistics process is represented by a rapid increase of the pressure until reaching the maximum value and maintaining it till the moment when the propellant charge is completely burned [1]. In mathematical terms, this maintenance of the constant pressure value for a certain period of time is translated by obtaining the following equality $\frac{dp}{dt} = 0$, where $\frac{dp}{dt}$ – represents the pressure derivative in relation to time.Therefore, the ratio between the rate of volume increase behind the projectile (projectile velocity) and the rate of propellant gases formation must be constant. This desideratum can be achieved by using propellants with variable burning rate and complex geometries, with a strongly progressive burning after reaching the maximum pressure.
To achieve these requirements, the researchers community has observed a promising future in the additive manufacturing of propellant charges [4], [5], since through this process, complex geometries can be obtained and, at the same time, more types of propellants with different burning rates can be alternated in the manufacture process.
In this paper, an interior ballistic model was solved to examine the performance of a 152 mm caliber using a propellant grains charge, with a simple geometry, and obtained through additive manufacturing, firstly using two types and secondly three types of propellants with different burning rates. The results yielded a pressure curve with two respectively three local maximum points, which closely approximates the ideal ballistic cycle.

2. Burning of Charges of Propellant Grains Obtained through Additive Manufacturing

For this paper, a propellant charge was chosen that incorporates two types of propellant with different burning rates. The propellant grain was designed with a simple cylindrical shape, in which the propellant grain, on the thickness e_1, burns at a slower rate compared to the second type. In such a grain, when the transition from one layer to the other occurs, even if there is no increase of the burning surface, the gas flow rate increases due to the increase of the burning rate, resulting in an effect similar to an increase of the burning surface. When the transition from one layer to another occurs suddenly, this is manifested on the pressure curve by obtaining a new maximum local point on it, which may be smaller or bigger than the first one.
For this concept proposed for study, the energetic material of which the outer layer of the propellant grain is formed, is a mixture of 89.1% AND (ammonium dinitramide) with 10.9% PCL (polycaprolactone), and the inner layer 88.19% ADN with 10.81% PCL and 1% CuO (cooper oxide).

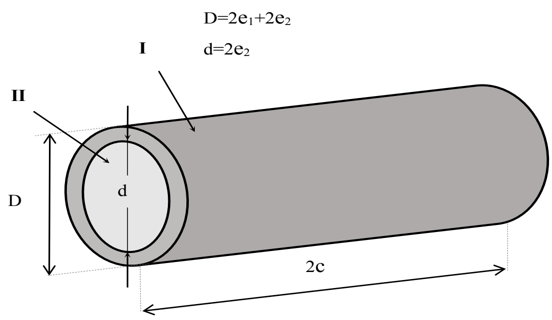

Figure 1: Cylindrical propellant grain, obtained through additive manufacturing using two different mixtures of energetic materials; D – grain diameter, d – the diameter of the second mixture of energetic materials, e_1 – the thickness of the outer layer, e_2 – the radius of the inner layer

Figure 1 shows that the propellant grain consists of two distinct types of energetic materials with the ends of the grain shielded. According to the existing literature [3] which indicates that the propellants burn in parallel layers, in this case the burning takes place only in radial direction. Therefore it is essential to note that the burning of the second type of material begins in the same moment of time when the burning of the first type was completed. Hence, in order to properly analyze the burning phenomenon, of this propellant grain, it is necessary to divide it into two distinct phases as follows:

- Phase I – lasts from the ignition of the propellant grain till the moment it has burned the thickness e_1;
- Phase II – commences after the thickness $e_1$of the propellant grain has burned and concludes when the burning front has travelled the distance e_2.

This division enables a more accurate analysis of the propellant burning process, taking into account the unique characteristics of the two different types of energetic materials present.

When it comes to propellant grain design, the shape coefficients of a grain with a simple geometry can usually be found in the existing literature [3]. However, the presence of two distinct energetic materials in one grain requires the determination of a new set of shape coefficients for each energetic material's geometry.

As per the law governing the formation of propellant gases, the combustion of propellants results in gases that have a mass equal to the mass of the burned propellant [3]. Therefore, to establish the gas formation law, two parameters will be used, namely the volume fraction of the burned propellant, ψ and the relative thickness of the burned propellant, .

$$(\psi)_i = \frac{(\omega_b)_i}{\omega} = 1 - \frac{(\Lambda)_i}{\Lambda_0} \qquad (1)$$

where, $(\psi)_i$ – the volume fraction of the burned propellant at ith time,$(\omega_b)_i$ – the mass of burned propellant at ith time, ω – the initial mass of propellant, $(\Lambda)_i$ – the volume of propellant grain at ith time and Λ_0 – the initial volume of propellant grain.

$$(z)_i = \frac{(e)_i}{e_1} \qquad (2)$$

where, $(z)_i$ – the relative burned propellant thickness at the ith time, $(e)_i$ – the burned propellant thickness at the ith time and e_1 – represents the thickness of the outer layer of propellant.

A typical way to express the correlation between the volume fraction of burned propellant and the relative burned propellant thickness is through a third-degree polynomial equation, in which χ, λ and μ are the shape coefficients of the propellant grain [6].

$$(\psi)_i = \chi(z)_i[1 + \lambda(z)_i + \mu(z)_i{}^2] \qquad (3)$$

In order to determine the shape coefficients of the propellant grain, firstly needs to derive the equations presented above with respect to time, and then equate equations (1) and (3). To better understand the process for determining the specific shape coefficients of phase I, an algorithm will be drawn up. Thus, by referring to Figure 1, we can determine the initial volume of the energetic material that belongs to phase I.

$$\Lambda_0 = 2c\pi\left(\frac{D}{2}\right)^2 - 2c\pi\left(\frac{d}{2}\right)^2 = 2c\pi \cdot \dots$$
$$\dots \cdot (d \cdot e_1 + e_1{}^2) \qquad (4)$$

and also the volume of propellant grain at ith time, $(\Lambda)_i$:

$$(\Lambda)_i = 2c\pi\begin{pmatrix} d \cdot e_1 + e_1{}^2 - d \cdot (e)_i - \cdots \\ \dots - 2e_1(e)_i + (e)_i{}^2 \end{pmatrix} \qquad (5)$$

Replacing (4) and (5) in equation (1) and making some advantageous transformations, we will obtain:

$$(\psi)_i = \frac{(e)_i \cdot (d + 2 \cdot e_1) - (e)_i{}^2}{de_1 + e_1{}^2} \qquad (6)$$

Differentiating equations (3) and (6) with respect to time and then equating the resulting equations yields:

$$\left[\frac{2e_1+d}{e_1{}^2+e_1 d}-\frac{2e}{e_1{}^2+e_1 d}\right]\frac{de}{dt}= \left[\begin{array}{l}\frac{\chi}{e_1}+\frac{2\chi\lambda e}{e_1{}^2}+\ ... \\ ...+\frac{3\chi\mu\, e^2}{e_1{}^3}\end{array}\right]\frac{de}{dt} \quad (7)$$

Solving equation (7), the shape coefficients of the propellant grain specific to phase I of burning are determined, obtaining the following set of coefficients:

$$\begin{cases}\chi_1 = 1+\frac{e_1{}^2}{e_1{}^2+e_1 d} \\ \lambda_1 = -\frac{e_1{}^2}{2e_1{}^2+e_1 d} \\ \mu_1 = 0\end{cases} \quad (8)$$

For the second phase of burning, following the same algorithm, the shape coefficients for the inner propellant layer will be:

$$\begin{cases}\chi_2 = 2 \\ \lambda_2 = -\frac{1}{2} \\ \mu_2 = 0\end{cases} \quad (9)$$

As mentioned earlier, the burning of the propellant charge will take place in two phases, first the burning of the first type of propellant occurs, followed by the second type. Therefore, the mass of the entire charge can be written in the following form:

$$\omega = \omega_1 + \omega_2 \quad (10)$$

where, ω_1 – the mass of the outer propellant layer, and ω_2 – the mass of the inner propellant layer.
To maintain the mass proportions consistent with the geometry, we need to:

$$\omega_1 = n \cdot \delta_1 \cdot \Lambda_{01} \quad (11)$$

$$\omega_2 = n \cdot \delta_2 \cdot \Lambda_{02} \quad (12)$$

where, Λ_{01} and Λ_{02}– the initial volume of these two mixtures of energetic materials for one propellant grain, δ_1 and δ_2– the solid propellant density of these two mixtures of energetic materials, and finally n – the number of propellant grains.
The equation for the volume fraction of burned propellant and the equation for the relative thickness of the burned propellant for the entire propellant charge will be determined by considering the previously calculated shape coefficients and the mass proportion of each propellant type.

$$\psi = \frac{\omega_1}{\omega}\psi_1 + \frac{\omega_2}{\omega}\psi_2 = \frac{\omega_1}{\omega}\chi_1 z_1(1+\lambda_1 z_1 + ... + \mu_1 z_1{}^2) + \frac{\omega_2}{\omega}\chi_2 z_2(1+\lambda_2 z_2 + \mu_2 z_2{}^2) \quad (13)$$

$$z = \frac{\omega_1}{\omega}z_1 + \frac{\omega_2}{\omega}z_2 = \frac{\omega_1}{\omega}\frac{e'}{e_1} + \frac{\omega_2}{\omega}\frac{e''}{e_2} \quad (14)$$

where, ψ_1 and ψ_2 – represents the volume fraction of burned propellant for outer and inner propellant layer, e' and e'' – the burned propellant thickness for each propellant layer at the i^{th} time from the web thickness e_1 respectively e_2 of the propellant.
One intermediate step for validating the approach used to determine the new sets of shape coefficients and the premise that the combustion of these two types of propellants is not simultaneous is to perform a numerical calculation of interior ballistics at constant volume. This step is necessary to ensure the accuracy of the overall interior ballistics model. By using a closed vessel with an interior volume of $40\ cm^3$ and a charge of $7.9\ g$, a predictor method was used to calculate various values including the burning rate, the pressure, the relative burned thickness, the volume fraction of burned propellant and the progressivity coefficient of the propellant shape. To obtain the pressure variation and the progressivity coefficient of the propellant shape in the closed vessel, the equations from the literature [3] were customized.

$$p = \frac{f_1\omega_1\psi_1 + f_2\omega_2\psi_2}{W_\psi} + p_a \quad (15)$$

where, p – the resulting pressure from the combustion of the propellant charge, f_1 and f_2 – the impetus for each propellant type, p_a – the priming pressure, and W_ψ – the volume of the loading chamber available for propellant gas.

$$W_\psi = W_0 - \frac{\omega_1}{\delta_1}(1-\psi_1) - \alpha_1\omega_1\psi_1 - \ldots$$
$$\ldots - \frac{\omega_2}{\delta_2}(1-\psi_2) - \alpha_2\omega_2\psi_2 \quad (16)$$

where, W_0 – the volume of the closed vessel and α_1 respectively α_2 – the propellant covolume for each energetic material.

Knowing the propellant characteristics for each energetic material from NASA CEA thermochemical equilibrium software [7], finding out the variation of the volume fraction of burned propellant for each energetic material, and the variation of the pressure we can determine the theoretical progressivity coefficient of the propellant shape.

$$\sigma(\psi) = \frac{\omega_1}{\omega}\sigma_1(\psi_1) + \frac{\omega_2}{\omega}\sigma_2(\psi_2) = \frac{\omega_1}{\omega}\frac{d\psi_1}{dt}\cdot\frac{\Lambda_{01}}{S_{01}}\cdot\frac{1}{A_1\cdot p_1^{\upsilon_1}} + \frac{\omega_2}{\omega}\frac{d\psi_2}{dt}\cdot\frac{\Lambda_{02}}{S_{02}}\cdot\frac{1}{A_2\cdot p_2^{\upsilon_2}} \quad (17)$$

where, S_{01} – the initial burning surface for the outer layer, S_{02} – the initial burning surface for the inner layer, A_1 respectively A_2 – stand for the burning rate coefficients and υ_1 respectively υ_2 – the exponential coefficients of the burning rate.

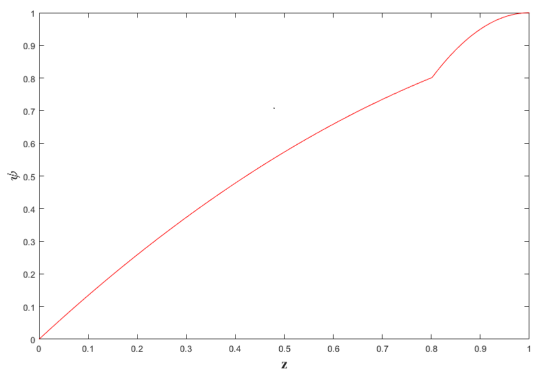

Figure 2: The volume fraction of burned propellant as a function of the relative burned propellant thickness

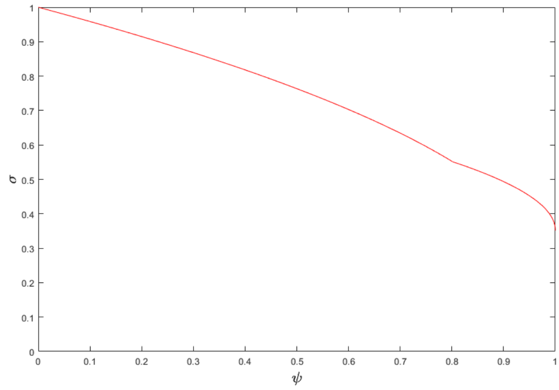

Figure 3: The progressivity coefficient of the propellant shape as a function of the volume fraction of burned propellant

The inflection point observed in the graphs of Figure 2 and Figure 3 represents the transition of the combustion front from the outer propellant layer to the inner propellant layer. This indicates that using a layered propellant grain, where the inner layer has a higher burning rate than the outer layer, can increase the progressivity of the burning even if in this case the burning surface decreases.

Hence, the approach proposed in this study, could serve as a basis for enhancing the performance of propellant charges. Furthermore, taking into account additive manufacturing capabilities, in addition to the possibility of using various energetic materials, it is feasible to manufacture propellant grains with complex geometries by creating voids inside the grains to control the burning surface, resulting in a more progressive burning process and more efficient.

3. Solving the Interior Ballistic Model for Charges of Propellant Grains Obtained through Additive Manufacturing

The direct problem of interior ballistics involves determining the variations of pressure and velocity with respect to the space traveled by the projectile in the barrel and time. To solve this issue, it is crucial to have a good understanding of the key events that occur during the firing process such as the burning of the propellant charge and the resulting gas formation, as well as the conversion of thermal energy from the propellant into kinetic energy to move the projectile.

To simplify the complex nature of the firing phenomenon, a system of equations is constructed by adopting a series of simplifying hypotheses [3] that aim to obtain simple relations that are easy to interpret and apply such as:

- the combustion of the propellant takes place according to the geometric law;
- the pressure at which the propellant burns is seen as an average pressure;
- the secondary mechanical works is proportional to the main mechanical work of the projectile's translation, and can be assessed by using a fictive mass coefficient φ, which is constant;
- the composition of the propellant gases remains unchanged, which enables the constant values of propellant impetus f and covolume α to be considered;
- the combustion of propellant charges initiates only after the primer mixture has burned, which leads to an increase of pressure in the chamber top_a;
- the index $\theta = \gamma - 1$ is considered constant, although it varies with the temperature of the propellant gases.

The basis of the developed mathematical model consists of the system of differential equations of the firing phenomenon written in t argument [3], as follows:

$$\begin{cases} \frac{dV}{dt} = \frac{sp}{\varphi q} \\ \frac{dl}{dt} = V \\ \frac{de}{dt} = Ap^{\upsilon} \end{cases} \tag{18}$$

Given that the propellant charge used in this study has a specific geometry, as shown in Figure 1, which consists of two energetic materials that burn sequentially, where the burning of the second material starts after the first material is completely burned, the mathematical model of the firing phenomenon can be described by adapting some equations from the literature, as follows:

- for the variation of the volume fraction of burned propellant we will use the eq. (13);
- for the variation of the relative thickness of the burned propellant we will use the eq. (14);
- the pressure variation within the gun barrel for this propellant charge concept can be expressed as follows:

$$p = \frac{f_1\omega_1\psi_1 + f_2\omega_2\psi_2 - \frac{\theta\varphi qV^2}{2}}{W} + p_a \tag{19}$$

where, q – the projectile mass, V – the projectile velocity and W–the volume behind projectile available for propellant gas

$$W = W_{\psi} + sl \tag{20}$$

where, W_{ψ} – is the volume of the loading chamber available for propellant gas from eq. (16), s – the barrel cross section area and l – the space travelled by projectile inside of the barrel.

Taking into account the particularities of the propellant grain used in this study and the initial premise from which the interior ballistics problem started in this case, the algorithm presented in [8] was customized. The volume fraction of the burned propellant was calculated based on the relative thickness of the burned propellant, z, and the relative rate with which the combustion front moves in order to consume the entire propellant grain, $\frac{dz}{dt}$.

So, as long as the first type of energetic material has not been completely burned, we will have the following conditions: $z_1 < 1, z_2 = 0, \frac{dz_2}{dt} = 0$ and $\psi_2 = 0$;

$$dz_1 = \frac{p(i)}{I_{k1}} dt \tag{21}$$

where, t – stands for time,$I_k = \int_0^{t_k} p^{\upsilon} dt$ – the total impulse of the gases, t_k – the necessary time to burn the entire propellant charge, and I_{k1} respectively I_{k2} – the total impulse of the gases for each energetic material.

Further, the variation of the relative thickness of the burned propellant can be determined.

$$z_1(i+1) = z_1(i) + dz_1(i) \tag{22}$$

and also, the volume fraction of burned propellant;

$$\psi_1(\mathrm{i}+1) = \chi_1 z_1(i+1)[1 + \lambda_1 z_1(i+1) + \ldots + \mu_1 z_1(i+1)^2] \tag{23}$$

If the burning of the first type of energetic material has been completed, $z_1 = 1$and also $\psi_1 = 1$, the burning of the second type begins, until the entire charge has burned completely$z_2 = 1$. So, rewriting the algorithm for the second type of energetic material, we will have:

$$dz_2 = \frac{p(i)}{I_{k2}} dt \tag{24}$$

$$z_2(i+1) = z_2(i) + dz_2(i) \tag{25}$$

$$\psi_2(\mathrm{i}+1) = \chi_2 z_2(i+1)[1 + \lambda_2 z_2(i+1) + \ldots + \mu_2 z_2(i+1)^2] \tag{26}$$

The integration of these two phases of combustion into a single phase was achieved by using eq. (13) and (14). Afterward, the pressure variation inside the gun barrel was determined using eq. (19), and the projectile velocity was determined by numerical integration of the translational motion of the projectile in the barrel:

$$\varphi q \frac{dV}{dt} = sp \tag{27}$$

where, $\varphi = 1{,}04 + \frac{1}{3} \cdot \frac{\omega}{q}$ – the fictive mass coefficient.

The propellant charge used in this study, shows two phases of combustion as detailed in the aforementioned algorithm. To provide a comparison, the graph generated under identical loading and maximum pressure conditions is included, but using cylindrical grains composed of a single energetic material, specifically 89.1% DNA with 10.9% CPL.

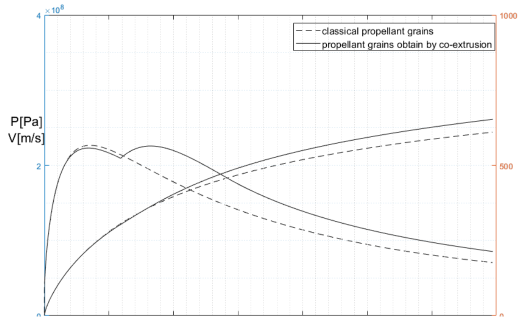

Figure 4: Pressure and velocity as a function of the space travelled by the projectile in the barrel

The graph in Figure 4 illustrates the pressure and projectile velocity variation in the gun barrel for a propellant charge formed from a single energetic material, represented by a dotted line, and a charge of propellant grains obtained through additive manufacturing using two mixtures of energetic materials with different burning rates, represented by a continuous line. Based on the curves shown in the graph, it can be observed that the use of layered propellant grains, with a higher burning rate of the inner layer, results in two local maximum points on the pressure curve. This leads to an increase in the area below the pressure curve, which in turn increases the mechanical work done by the propellant gases to move the projectile, resulting in a higher muzzle velocity.

Based on the presented algorithm, the interior ballistics was carried out for a propellant charge with grains with the same gabarit dimensions, but consisting of 3 different energetic materials, in which through the third energetic material, DNA 87.3% with CPL 10.7% and 2% CuO a surplus of 11.8% is added to the propellant charge.

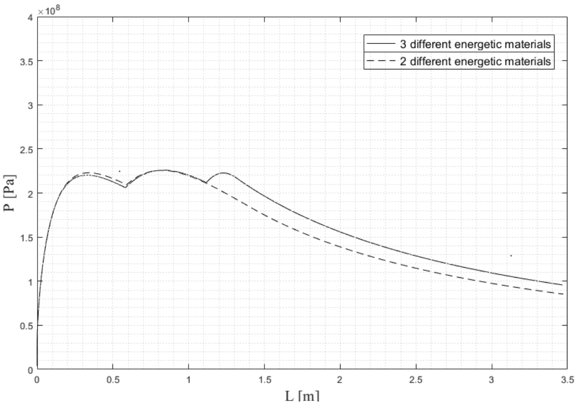

Figure 5: Pressure as a function of the space travelled by the projectile in the barrel

Observing the pressure curve obtained from a propellant charge composed of three-layered grains, we can notice the emergence of three local maximum points, one for each type of energetic materials mixture. This characteristic results in the pressure being sustained at high values for a longer period of time, which closely approximates the ideal ballistic cycle, and also results in a superior mechanical work performed by the propellant gases.

4. Conclusions

In this paper, it was demonstrated that by using propellant grains obtained through additive manufacturing using several energetic materials in which their vivacity increases from the outer layer to the inner layer, the progressivity coefficient of the propellant shape increases even though the combustion surface decreases.

The interior ballistics model was modified for the proposed concept, resulting in a pressure curve that exhibits three local maximum points, which closely approximates the ideal ballistic cycle.

The use of charges of such propellant grains, through which the energetic materials are alternated, leads to the improvement of weapon systems because without exceeding the limits imposed regarding the maximum pressure in the gun barrel, by successively obtaining several local maximum points for the pressure, the overall value of the pressure is greater, which leads to obtaining a higher mechanical work performed by the propellant gases and thus obtaining greater ranges for target engagement.

Taking into account the capabilities of the additive manufacturing, a perspective would be the development of a method for determining the complex geometries of the propellant grains, which present a highly progressive combustion. Such grains are expected to maintain a constant pressure curve from the point of reaching the maximum pressure until the propellant charge is completely burned.

Acknowledgements

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