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Mechanical and Ballistic Properties of Spherical Single Base Gun Propellant

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Abstract: The effect of the initial temperature on the mechanical properties of spherical single base gun propellant was investigated by means of a compression test, which consisted of compression of a propellant bed conditioned at various initial temperatures. Following this mechanical treatment, the pressed grains (after thermal conditioning at ambient temperature) were tested in a closed vessel. The results from the combination of compression and closed vessel tests supported the assumption that there are two phenomena occurring inside the cartridge at low temperatures which compensate each other; the first is a decrease in the burning rate as the initial temperature is decreased, and the second is grain fracturing occurring on ignition. Additionally, a specific parameter, the specific surface area, turns out to be an appropriate parameter for quantifying the mechanical damage to the propellant grain resulting from the compression test. Tests on the aged propellant have also been conducted.

Keywords: mechanical properties, firing temperature, gun propellant, ageing, ballistic firing, closed vessel tests

List of symbols

σ_r [%/°C]	The temperature coefficient of the burn rate defined in [8]
A_{rel} [%]	Relative surface area
L [1/MPa·s]	Dynamic vivacity
L_{rel} [%]	Relative dynamic vivacity
T_0 [°C]	Conditioning temperature of the propellant before the ballistic and closed vessel tests (T_0 = 71 °C, 21 °C, −20 °C and −54 °C)

T_C [°C]	Conditioning temperature of the propellant before the compression tests (T_C = 71 °C, 21 °C and −54 °C)
z [-]	Burn fraction

1 Introduction

In a previous study [1] we noticed that the influence of the initial temperature on the peak pressure inside a cartridge is not fully explained by the temperature sensitivity of the burning rate of the propellant, especially at low temperatures. We speculated that the investigated propellant is more brittle at these low temperatures and that the phenomenon of grain break-up under the ignition conditions becomes likely. These grain fractures may in turn lead to an increase in the burning surface area, compensating for the drop in the burning rate when the temperature is decreased and eventually resulting in an increased peak pressure.

There has been interest for some considerable time in the mechanical properties of propellant materials over a wide range of strain rates, stress conditions and temperatures [2, 3]. Some authors have postulated that the temperature sensitivity of gun performance could be related to variations in the mechanical properties of the propellant grains with the ambient temperature [4-6]. In fact, at low temperatures, close to or below the glass transition temperature of the propellant (as an example, the glass transition temperature of a double base propellant has been measured and found to be −32.5 °C [7]), the propellant grains become brittle and grain break-up can occur on ignition and early pressurisation inside the gun [8, 9].

The aim of the present study was to support this assumption by investigating the temperature sensitivity of the mechanical properties of the propellant in order to highlight the role played by both the combustion and mechanical properties of the propellant on the temperature sensitivity of gun performance.

An important diagnostic for laboratory experimentation involves the use of a closed vessel, in which the pressure history of a burning propellant is recorded. From the pressure history, information concerning the combustion behaviour of the propellant (*i.e.* dynamic vivacity) can be deduced. Dynamic vivacity has been used to assess propellant grain surface area behaviour during combustion [10]. For this reason, we decided to investigate the effect of the initial temperature on the mechanical properties of a spherical single base gun propellant by a combination of compression and closed vessel tests.

2 Previous Experimental Observations

Detailed data and experimental procedures for the abridged set of results presented in this paper can be found in Refs. [1] and [11].

2.1 Tested propellant

Spherical single base propellant was used in our previous investigation. The spherical single base propellant had an average diameter of 553 μm. It contained around 10% of nitroglycerin, it was stabilised with diphenylamine (DPA), and the average concentration of the deterrent dibutyl phtalate (DBP) was 4.8%. The composition of the investigated propellant is given in Table 1.

Table 1. Composition of the propellant investigated

Component	Composition [wt.%]
NC	81.52
H_2O	0.66
KNO_3	1.2
NGL	10.7
DBP	4.8
DPA	0.59
NDPA	0.53

NC: Nitrocellulose, NGL: Nitroglycerin, DBP: Dibutyl phthalate, DPA: Diphenylamine, NDPA: Nitrodiphenylamine.

2.2 Closed vessel results

Figure 1 shows the influence of the initial temperature on the burning rate as reported in [11]. It may be observed that the burning rate decreases with the conditioning temperature of the propellant.

We assessed that for the spherical single base propellant studied, the sensitivity of the burning rate to the initial temperature σ_r was equal to:

- 0.305%/°C (towards high temperatures),
- 0.121%/°C (towards low temperatures).

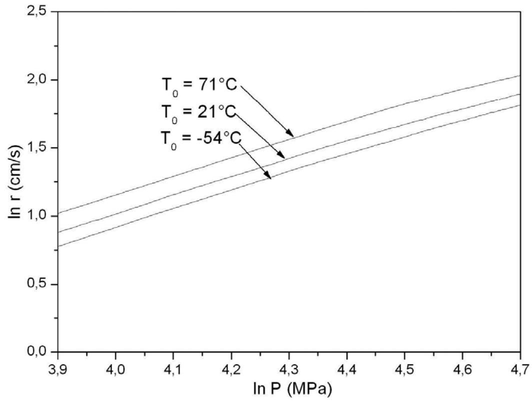


Figure 1. Temperature dependence of the burning rate for the spherical single base propellant [11]

2.3 Ballistic firing

Figure 2 shows the variation of the maximal pressure inside the cartridge as a function of the initial temperature for unaged and aged propellant (aged for 30 days at 71 °C) as obtained in our previous study [1].

For unaged propellant, in the range of high temperatures (71 °C/21 °C), the maximal pressure inside the cartridge increased as the initial temperature of the propellant increased. This is in accord with the variation of the combustion rate between 71 °C and 21 °C (Figure 1).

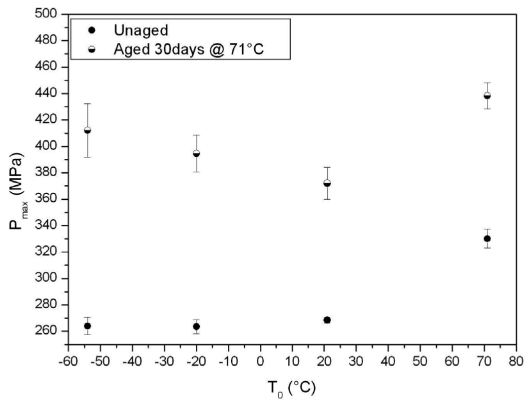


Figure 2. Variation of the maximal pressure inside the cartridge as a function of the initial temperature of the unaged and aged (30 days at 71 °C) propellant (10 shots), the displayed error bars are ±1 standard deviation (SD)

For lower temperatures (21 °C/−54 °C), a nearly constant value of the maximal pressure was observed (Figure 2). This does not correlate adequately with the burning rate measurement. We speculate that this is related to the fact that there are two phenomena compensating for each other:

(1) The first is the decrease of the burning rate as T_0 decreases and contributes to a drop in the maximal pressure in the cartridge.

(2) The second is grain fracture due to brittleness of the propellant particles at low temperatures, and occurs at ignition. In fact, once ignition of the propellant charge occurs, local bed compaction associated with the ignition wave or by grain impact against, most likely, the projectile base, can lead to local regions of high loading density. In these local regions, intergranular stress occurs and results in grain fracture [9]. The result of this will be an increased burning surface, potentially compensating for the drop in the burning rate of the propellant when the temperature decreases (Figure 1). In this situation, the final result is a nearly constant value of the maximal pressure.

After ageing the increase in the maximal pressure is greater for the low temperatures (−54 °C and −20 °C, Figure 2). We speculated on the likely amplifying effect of grain fracture occurring at low temperature after ageing. The importance of the increase of the maximal pressure inside the cartridge with ageing is illustrated in Table 2, by the difference (expressed as a percentage) between the maximal pressure inside the cartridge of the aged propellant and the maximal pressure inside the cartridge of the unaged propellant.

Table 2. Increase in percentage of the maximal pressure inside the cartridge from unaged to aged (30 days at 71 °C) propellant. The values given are for different initial temperatures of the propellant

T_0 [°C]	71	21	−20	−54
ΔP_{max} [%]	32	38	50	56

3 Methodology

The previous experimental observations (see Section 2) demonstrated the potential importance played by the mechanical properties of the single base propellant on the gun performance as a function of T_0, especially at low temperatures.

The effect of the initial temperature of the single base propellant on its mechanical properties was investigated by means of a compression test, which consisted of the compression of a propellant bed conditioned at various initial temperatures ($T_C = 71$ °C, 21 °C and −54 °C). Following this mechanical treatment, the pressed grains (after thermal conditioning at ambient temperature) were fired in a closed vessel. Compression of the propellant is relatively simple to achieve and provides a good indication of the propellant bed behaviour during the first stages of ignition and combustion in a gun [12].

In the following sections of this paper, uncompressed propellant was tested at $T_0 = 21$ °C and is referred to as "benchmark".

The tested propellant is the same as the one used in our previous investigation (see Section 2.1). Tests on the aged propellant (30 days at 71 °C) were also performed.

4 Burning Properties before and after Mechanical Treatment

4.1 Properties before mechanical treatment

For technical reasons, the closed vessel used in this investigation was slightly different from the one used in our previous study [11], the main difference being the internal volume (42 cm^3 instead of 118 cm^3). The current operating conditions are given in Table 3.

Table 3. Operating conditions of the closed vessel tests

Vessel volume [cm^3]	42
Propellant mass [g]	1
Loading density [g/cm^3]	0.02
Propellant conditioning T_0 [°C]	−54, 21, 71
Ignition method	0.5 g black powder

The black powder ignition system consisted of two electrodes, which were connected with a filament. The latter runs through a plastic capsule filled with black powder. The filament connecting the two electrodes ignites the black powder by the Joule effect, when an electric current is passed. To ensure an efficient ignition of the black powder, the plastic capsule should be filled with sufficient black powder (0.5 g in this case). We assumed that even the mass of the black powder, which makes up 50% of the tested propellant (Table 3), does not affect the pressure rise curve. In fact, the pressure produced by the combustion of the black powder alone has been measured and compared to the maximal pressure produced when the propellant is tested; it represents only 6% of the maximal pressure. Additionally, the burning rate and vivacity were analysed in the range of 30-70% of the maximal pressure inside the closed vessel.

The outputs from the closed vessel tests, burning rate and dynamic vivacity, were calculated according to STANAG 4115 [13].

4.1.1 Burning rate and temperature coefficient

Figure 3 shows the variation of the burning rate as a function of the initial temperature. Qualitatively similar variations of the burning rate with T_0 were observed (see Figure 1).

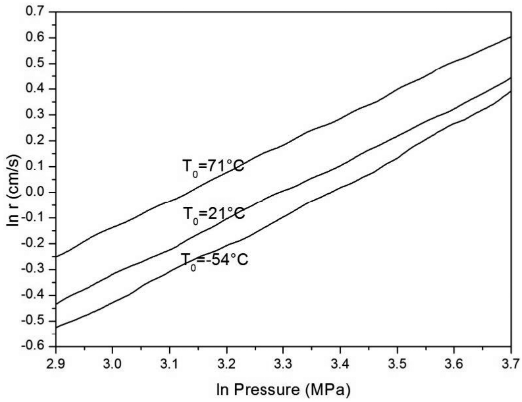


Figure 3. Temperature dependence of the burning rate for the spherical single base propellant

The temperature coefficients σ_r over the experimental range of temperatures are given in Table 4. It was observed that the change of operating conditions of the closed vessel tests (Table 3) did not significantly affect the temperature sensitivity σ_r (see values mentioned in p. 2.2).

Table 4 Values of the temperature coefficient (σ_r) at various pressures. Values in parenthesis are *one* standard deviation (1SD)

Pressure [MPa]	σ_r [%/°C]	
	71 °C/21 °C	21 °C/−54 °C
20	0.317	0.120
25	0.333	0.109
30	0.331	0.115
35	0.307	0.092
40	0.310	0.107
Average	0.319 (±4%)	0.110 (±9%)

Although the closed vessel tests were carried out under different operating conditions, we arrived at the same conclusions both qualitatively and quantitatively. This is an interesting collateral conclusion of this investigation: the results from our previous study [11] were confirmed with these test results, obtained using a different sized closed vessel.

4.1.2 Dynamic vivacity

Figure 4 shows the dynamic vivacity of the propellant as a function of T_0. As in the case of the variation of the burning rate, it may be noticed that the vivacity of the propellant increases as the initial temperature increases.

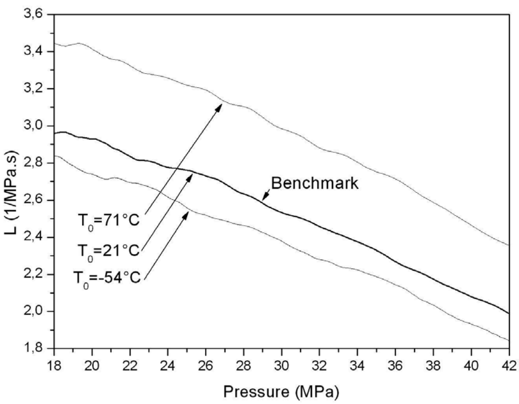


Figure 4. Temperature dependence of the dynamic vivacity

4.2 Mechanical treatment: compression of the propellant bed

The propellant beds were conditioned for a minimum of 8 h at 71 °C, 21 °C and −54 °C (T_C), then removed from the conditioning cabinet and compressed immediately (Figure 5) at a pressure maintained at 100 bar during one minute using a manual hydraulic press. The mass of each batch of propellant bed was equal to 1 g. Figure 6 shows pictures of the spherical single base propellant grains before (Figure 6a) and after mechanical treatment (Figure 6b). The pictures were taken with an optical microscope.

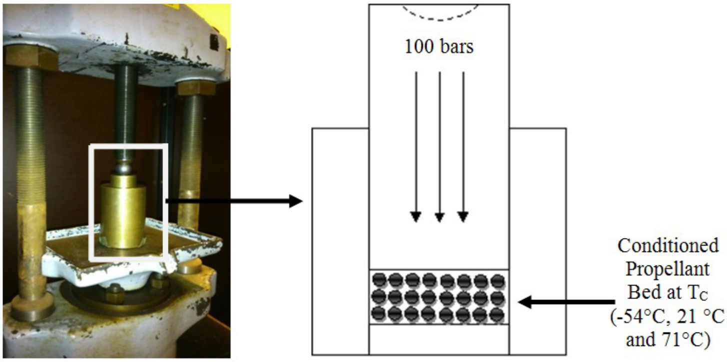
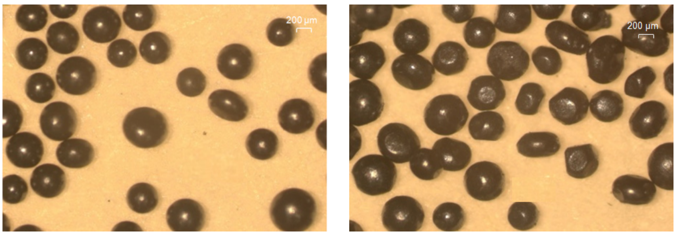


Figure 5. Compression of the conditioned propellant beds (T_C) at a pressure of 100 bar for 1 min using a manual hydraulic press. The conditioning temperatures (T_C) were equal to −54 °C, 21 °C and 71 °C. The mass of the propellant bed was 1 g



a b

Figure 6. Photomicroscopy of (a) the spherical propellant grains, and (b) grains from the compressed propellant bed

4.3 Properties after mechanical treatment

After mechanical treatment at their respective temperature T_C, all of the samples were conditioned at ambient temperature (21 °C) and fired in the closed vessel. The operating conditions were identical to those mentioned in Section 4.1.

Only the dynamic vivacity of the previously compressed propellant can be determined and discussed. The reason for not being able to determine the burning rate is the change in shape and grain size of the propellant after the compression tests (Figure 6). This change of shape cannot be quantified and, consequently, the form function cannot be calculated, and thus neither can the burning rate.

The effect of the mechanical stress (compression) on the physical parameters of the propellant has not been investigated. We assumed that the compression does not have a significant impact on the force and covolume. Indeed, the maximal pressures obtained by burning uncompressed and compressed propellant inside the closed vessel were the same. Additionally, the physical parameters (propellant density, force and covolume) are not input data needed for the determination of the dynamic vivacity. Note that the study in this paper is based on the influence of compression on the dynamic vivacity.

4.3.1 Dynamic vivacity

In order to observe the influence of compression on the combustion behaviour of the propellant, the dynamic vivacities of the uncompressed propellant tested at $T_0 = 21$ °C (benchmark) and the compressed propellant at various initial temperatures are plotted in Figure 7. It may be observed that the vivacity of the propellant increases and keeps its overall behaviour as a function of pressure, after compression.

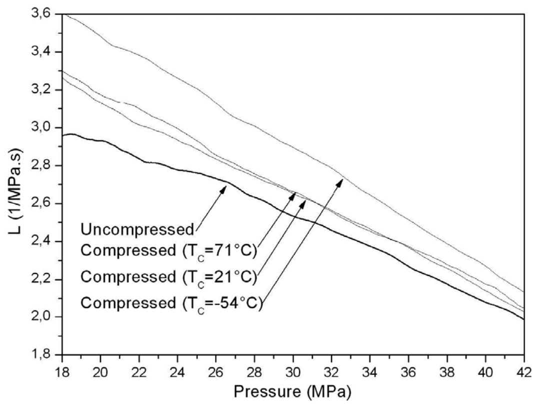


Figure 7. The dynamic vivacity of the uncompressed propellant tested at $T_0 = 21$ °C (*benchmark*) and the compressed propellant at various initial temperatures (T_C)

It is clearly noticed that at low temperature ($T_C = -54$ °C), the effect of compression on the dynamic vivacity is greater than at medium and high temperatures. Indeed, the increase in the vivacity of the propellant after compression at −54 °C (T_C) is sharper than the increase of the vivacity of the propellant after compression at 21 °C and 71 °C (T_C). Basically, we did not notice any significant difference between the vivacity of the treated propellant when fired at 21 °C and 71 °C.

At low temperature, the two phenomena (1) and (2) mentioned in Section 2.3 are in competition. In Figure 8 we have illustrated this competition by isolating the two effects from the benchmark:

- Curve (1): effect of the initial temperature T_0, no pre-mechanical treatment. The decrease in vivacity resulting from the low firing temperature implies a reduced peak pressure in the combustion chamber.
- Curve (2): effect of the mechanical treatment, no change of initial firing temperature. The increase in vivacity resulting from the mechanical compression at low temperature implies an increased peak pressure in the combustion chamber.

In actual gun firings using cartridges at low temperature, both effects occur and lead, in the case investigated, to a nearly constant value of the peak pressure (Figure 2).

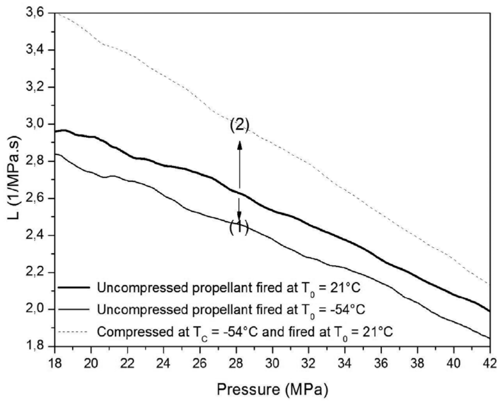


Figure 8. Effects on the dynamic vivacity: (1) decrease of the initial temperature, and (2) compression at −54 °C

4.3.2 Relative surface area

In order to quantify the damage to the propellant grains resulting from the mechanical treatment, the "relative surface area" A_{rel}, may be defined [12]. The determination of A_{rel} requires initially the calculation of the relative vivacity, as defined by Equation 1:

$$(L_{rel})_z = \left(\frac{L_{T_C}}{L_{benchmark}}\right)_z \tag{1}$$

where:

- L_{TC} is the dynamic vivacity of the compressed propellant at T_C, tested at $T_0 = 21$ °C,
- $L_{benchmark}$ is the dynamic vivacity of the uncompressed propellant tested at $T_0 = 21$ °C,

- z is the burn fraction which is approximated by P/P_{max}.

The characteristic value A_{rel} is then determined by extrapolation to z = 0 of the change in relative vivacity calculated between z = 0.3 and z = 0.7. The relative surface area (A_{rel}) is a good quantification of the mechanical damage undergone by the propellant grains. For undamaged propellant grains, A_{rel} is equal to 100%. For damaged propellant grains this value is larger. The relative vivacities and A_{rel} are represented in Figure 9.

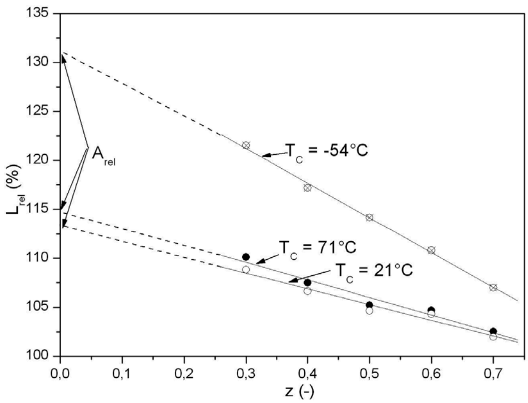


Figure 9. Relative vivacity as a function of the burn fraction at various initial temperatures (T_C)

In addition, the quantified values of the relative surface area over the experimental range of temperatures are given in Table 5. The quantified relative surface area (Figure 9 and Table 5) is a convincing demonstration that:

- Mechanical constraints have a different influences on the grain behaviour at low temperature from the one at ambient temperature.
- Mechanical constraints at higher temperatures do not have an influence on the grains other than the one observed at ambient temperature.

Table 5. Results of the compression tests: relative surface areas. R^2 represents the correlation coefficient of the linear relative vivacity

T_C [°C]	A_{rel} [%]	R^2
71	115	0.981
21	113	0.980
−54	132	0.998

4.3.3 Influence of ageing

The values of the relative surface area of the propellant aged for 30 days at 71 °C over the experimental range of temperatures are given in Table 6. A_{rel} increases with ageing, especially at low temperature, and indicates that ageing makes the grains more sensitive to mechanical constraints, especially at low temperature. This is consistent with the observed sharp increase in the maximal pressure in the gun combustion chamber when aged propellants are fired at low temperatures (Figure 2).

Table 6. Relative surface areas of the aged propellant (30 days at 71 °C), the value in parenthesis is the relative increase of A_{rel} due to ageing. R^2 represents the correlation coefficient of the linear relative vivacity

T_C [°C]	A_{rel} [%]	R^2
71	126 (+9%)	0.957
21	124 (+9%)	0.947
−54	152 (+15%)	0.953

5 Conclusions

At low temperatures, the variation of the maximal pressure inside a cartridge as a function of the initial firing temperature of the propellant cannot be fully explained by the burning rate properties alone. We speculate that the mechanical behaviour of the propellant grains at low temperatures also plays an important role in the overall ballistic properties of the round. This assumption is supported by the results from this investigation.

It has been clearly observed that the propellant grains are more sensitive to mechanical treatment at low temperatures. The parameter "Relative Surface Area" enabled us to quantify the discrepancy in vivacity resulting from mechanical constraints. As a consequence, we observed that the change in mechanical properties compensates for the decrease in the burning rate at low temperatures. In the case investigated, this compensation leads to propellant grains having similar ballistic behaviour at low and ambient temperature, accounting for their "insensitiveness" to the initial firing temperature. We have no evidence that the observed phenomenon will always lead to such a neutral behaviour, but we may state that adjusting this compensating effect would make it possible for the manufacturer to better control the ballistic properties of gun propellants at low temperatures.

Compression tests employing aged propellants demonstrated that the propellant bed becomes more susceptible to damage under mechanical stress after ageing, especially at −54 °C.

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