Scale Effect on Composite Solid Propellant Burning Rate

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ABSTRACT

Ballistics analysis use sub-scale characterizations to determine ballistic performance predictions of large Solid Rocket Motor (SRM). It is now well admitted that the burning rate deduced from firing tests of full-scale motors differs from that measured in subscale motor work. Despite this difference is typically only a few percent, many parameters involve burning rate variations in full scale motor. The two main reasons of this variation are the real solid grain geometry at test firing and the manufacturing process.

Usually, the empirical parameters necessary to predict the performance of a motor are hump effect and scale factor. They are mainly linked to the manufacturing process and are deduced from the exploitation of previous firing tests. The objective of the study presented in this paper is to underline and to explain physical phenomena linked to those empirical parameters in order to be able, in the future, to simulate directly the ballistic behavior of a new motor.

One of the main impact of the manufacturing process on ballistic performance is due to the particle segregation in the propellant during the filling. A 2D study performed on a small scale SRM is presented. The global performance and the local behavior have been analyzed by means of firing tests and local measurements. The important influence of the manufacturing process on both global and local behavior has been clearly demonstrated. The experimental results have been compared to simulation results obtained using a new code developed at SNPE Propulsion to compute surface burnback in composite propellant. The input values necessary for the simulation have been deduced from filling simulation and NMR visualizations. The numerical model gives a really good prediction of both global and local behavior.

All these simulation results lead us to understand phenomena involved by casting process. Our objective now, is to carry on validations to be able to integrate this new surface burnback model into our performance predictions in order to take into account casting process effects. This new method will be particularly useful to predict the performance of a SRM in the event of anomalous filling and then help decide whether the motor may be used or not. It will also enable us to predict the performance of a new motor, before the first firing test while taking account of the casting process and to optimize the casting process to minimize these effects.

1.0 INTRODUCTION

For many years, SNPE has expended an important effort in the improvement of ballistic performance predictions of large Solid Rocket Motor (SRM) for both space and strategic propulsion [1,2]. As the rocket motor designer must have a good understanding of the variation of propellant burning rate, we can
consider it is one of the most important and, as it happens, the most difficult parameter to control. It has been widely reported that the burning rate deduced from firing tests of full-scale motors differs from that measured in sub-scale motor work. Despite this difference is typically only a few percent, many parameters involve burning rate variations in full scale motor. One of the main investigation fields is the study of the impact of the manufacturing process on the ballistic responses of the SRM. It is now well admitted that the ballistic performance of solid rocket motors depends on the process used to manufacture it. The main impact of the manufacturing process on ballistic performance is due to the particles segregation in the propellant during the filling. This heterogeneity of propellant leads to operating particularities like the hump effect and a large part of the scale factor. The impact of the manufacturing process on ballistic performance is the subject of several studies at SNPE. These studies concern the mechanisms of formation of heterogeneity, their characterization, and their integration in ballistic predictions. This last item has led to the development of two new numerical tools. The first one is a varying burning rate surface burnback computation code which is described in this paper. To be able to integrate the result of this computation in ballistic performance prediction it has also been necessary to develop a new ballistic performance prediction code. In the code MOPTI the ballistic performance is simulated by linking time step by time step the varying surface burnback simulation to a two-dimensional CFD simulation in the combustion chamber.

After a short definition of the empirical parameters usually necessary to predict the performance of a motor with a classical method, this paper presents a study concerning the impact of propellant burning rate anisotropy on ballistic performance. Its objective is to explain physical phenomena linked to those empirical parameters in order to be able, in the future, to simulate directly the ballistic behavior of a new motor.

Consequently, a small grain has been defined to study the impact of process on ballistic performance. Several grains have been manufactured with three different processes. One grain for each process has been fired, and another one has been cut in samples for local characterisations. The new varying burning rate surface burnback code has been used to simulate the performance of each grain. The results obtained for both firing tests and local measurements have been compared to the simulation results.

### 2.0 CLASSICAL BALLISTICS ANALYSIS

Usually, performance previsions are computed with a simplified ballistic model. The calculation of the steady state chamber pressure is done by the equalization of the mass flow rates: the first one from the combustion and the other one from the flow through the nozzle throat:

\[
\int \rho \, dv = Cd \cdot P \cdot At
\]

where \( \rho \) is the propellant density, \( S \) the combustion surface area, \( Cd \) the mass flow coefficient, \( P \) the chamber pressure and \( At \) the nozzle throat area.

Then, the thrust \( F \) is computed by:

\[
F = \eta \cdot Cf \cdot P \cdot At
\]

where \( \eta \) is the thrust efficiency and \( Cf \) the thrust coefficient.

Computing the mass flow generated from the propellant involves solving the problem of a front regression using the propellant burning rate.

Ballistics analysis use sub-scale characterization to determine the full scale prediction. Then, for the first firing of a new SRM, the burning rate is deduced from firing test of ballistic specimen. This first prediction, compared to the measured evolution is plotted on the Figure 1.
Then, the full scale burning rate is determined by introducing two correcting factors:

- A linear correction, often called **scale factor**.
- A non linear correction mainly resulting from the manufacturing process and usually called **hump effect**.

The comparison between the burning time computed from the theoretical prevision and the full scale firing test one determines the first correction constant.

This parameter represents the scale effect between a small scale motor and a full scale one. The corrected prediction, using this scale factor, is plotted on Figure 2.

The burning rate is finally corrected on each part of the web using a non linear normalised local rate ratio (called Hump effect).

The prediction resulting from the association of these two factors is presented on Figure 3 and is compared with the firing curve.
The burning rate depends on many intrinsic (combustion mechanism, type of propellant) and global parameters (engineering design).

Pressure, temperature, residence time, cross velocity and radiation for instance are partially controlled or estimated in small scale motor design and firing conditions definition.

All theses parameters influence both the linear and non linear corrections. However, for grain design purpose, both corrections are considered separately on the scale factor and the hump effect.

Many parameters involve burning rate variations in full scale motor, but they don’t have the same influence on the scale factor. Some of them can increase the scale factor and others decrease it. Scale factor between propellants tested in the same measurement systems sometimes vary by an order of magnitude of 8%. But it is impossible to correlate directly scale factor and web thickness.

One of the main reason of this variation is the real solid grain geometry at test firing. This parameter is predicted thanks to structural analysis and includes thermal shrinkage, pressure curing, firing position, firing pressure. Generally the grain deformation reduces the web thickness and increases the grain surface, and has thus an impact on the scale factor. This reduction is about 30%. The real grain geometry allows to decrease the dispersion of scale factor.

The second one is the manufacturing process[8]. In some configurations the difference in the burning rate value between two different processes, for example plunged mandrel grain and mandrel in place grain, is about 3%. It represents 50% of the scale factor (HTPB propellant).

Finally, the non explained part of the scale factor depends on insulation, thermoelastic coupling, acceleration, etc…

The Hump effect traduces the non linear burning rate variations along the web which can reach an amplitude of 10% around the mean value.

The hump effect curves corresponding to different grain design are presented on Figure 4.
Scale Effect on Composite Solid Propellant Burning Rate

Many other parameters disturb the hump effect: grain deformation, thermoeelastic coupling, ignition, tail-off phase, etc…but these parameters have to be considered of the second order.

Indeed, hump effect is mainly related to the manufacturing process and propellant formulation. It depends consequently on the scale of the grain considered. It is now widely admitted that the non polymerised propellant is submitted to shear stresses during casting process. These stresses induce separation of the solid particles and change the propellant local composition. This transformation leads to local burning rate variations\(^9\).

To conclude this part, sub-scale characterizations are not efficient enough to determine the full scale prediction. The full scale burning rate is finally determined by introducing two correcting factors called scale factor and hump effect. The manufacturing process effects have a great impact on these two parameters and then on the ballistic response of composite solid propellant grains.

### 3.0 PROCESSING EFFECTS ON BALLISTIC RESPONSE

Manufacturing process generates various shear stresses into uncurred composite propellant:

- Flow through pipes, slit plate and blowholes in the case of injection along the mandrels.
- Fall of free paste streams also tends to create high velocity gradients and shearing inside propellant mass in the vicinity of dropping zones.
- Spreading of propellant accumulated around dropping zones induces the moving of free surfaces (knit-lines zones).
- Plunging after casting can induce again shear stresses and a complete reorganisation of the propellant structure.
Different stresses induce separation of solid particles or charges of different sizes and then modify the local propellant composition. This modification involves local burning rate variations. Physical analysis and local burning rate measurements on samples have confirmed the burning rate profile derived from the grain firing analysis. The local burning rate analysis also confirms the non-isotropic burning rate behavior.

Once this phenomenon has been demonstrated, it has become necessary to integrate these burning rate variations in our performance predictions model. As a consequence, it was important to realize and to validate a new code enable to take into account casting process effects in order to be able, in the future, to simulate directly the ballistic behavior of a new motor.

In this study, from experimental observations, the approach we have chosen is the following. We first observe the effects. Then we try to reproduce the mathematical behavior in our performance predictions and finally validate our global model.

To go further, more detailed studies about burning mechanisms could be necessary.

3.1 Description of the Study

Experimental Study
In order to obtain experimental results to construct and validate a mathematical model, a small scale grain was defined. The objective of this experimental study was to show the impact of the manufacturing process on both global (firing test) and local (dissections) behavior and to simulate them.

The grain we have chosen for this study is presented on Figure 5.

The grain is inhibited on its external diameter.

Six grains have been manufactured in the same propellant batch using three different processes:

- Process A: Rotating casting around the mandrel,
- Process B: Rotating casting and plugged mandrel,
- Process C: Mandrel in place, three casting points around the mandrel.

Three of these grains have been fired, and the three others have been cut in samples for local characterizations.

The local characterizations were burning rate and density measurements, and Nuclear Magnetic Resonance (NMR) imaging visualisations.
Two experimental techniques have been used for the burning rate measurements: Strand Burner and ultrasonic measurements. In the first one, the sample has a parallelepipedal form (1x1x7cm) inhibited on all its faces except one end. The combustion is initiated in a pressurized tank and the combustion time between the two ends is measured. The mean burning rate on the entire length of the sample (7cm) is deduced. The sample used for ultrasonic measurements is a cylinder (diameter: 60mm – thickness: 30mm). The periphery is inhibited and the bottom face is connected to the ultrasonic sensor while, the combustion is initiated on the other one. This measurement gives the evolution of thickness and pressure versus time. Then, the evolution of burning rate versus sample thickness for a given pressure is deduced. The first technique uses smaller samples and then enables more numerous and more local measurements. On the other hand this method is less precise than the ultrasonic technique. An other advantage of the ultrasonic technique is to give the evolution of the burning rate along the web, and not only a mean value like the strand burner technique.

In the following, we distinguish the radial and the longitudinal burning rates. The first one corresponds to the burning rate along the web, and the second one is parallel to the bore. Using the ultrasonic technique, we are able to measure the burning rate profile along the web and its evolution on the height of the grain as it is shown on Figure 6 for the grains manufactured using the rotating casting.

**Figure 6: Cutaway Drawing of a Silvan Grain: Location of Burning Rate Samples.**

**Numerical Study**

The performance of this grain has been simulated using a varying burning rate surface burnback code developed by SNPE.

In our model, illustrated on Figure 7, the burning rate on one point of the combustion area depends on the local angle between the combustion front and a physical parameter characteristic of the uncured propellant flow organization. The burning rate has a minimum value for an angle of 0° and a maximum value for an angle of 90°.
Figure 7: Link between Propellant Heterogeneities and Burning Rate.

In this section, we shortly describe the numerical algorithm\cite{10,11,12,13} we use to compute the front position in the media described on Figure 7.

The computational domain is $\Omega$. The boundary is divided in two parts: $\Gamma_1$ which is inhibited and $\Gamma_2$ which is the location of the uninhibited points. We assume $\partial\Omega = \Gamma_1 \cup \Gamma_2$, so that the boundary points are either inhibited or uninhibited.

We describe the location of the front at time $t$ by the isoline $t=\Psi(x,y)$, $(x,y) \in \Omega$. This can be justified by mathematical arguments, provided that $R(\alpha)=1/v(\alpha)$ is regular enough and stays strictly positive. The model is:

$$
\begin{cases}
- R(\alpha(\nabla\Phi, \nabla \theta)) + \nabla \Psi = 0 & \forall t \geq 0 \quad x \in \Omega \\
- R(\alpha(\nabla\Phi, \nabla \theta)) + \nabla \Psi \geq 0 & \forall t \geq 0 \quad x \in \Gamma_1 \\
\Psi(x,y,z) = \phi_0(x,y,z) & (x,y,z) \in \Gamma_0
\end{cases}
$$

In equation (1), we have explicitly mentioned the relation between the front shape and the propellant flow organization.

This equation is a stationary Hamilton-Jacobi (HJ) equation. The numerical procedure we use relies on ideas widely used within the CFD community. First, we look for the solution of (1) as the steady solution of the HJ equation

$$
\begin{cases}
\phi_t - R(\alpha(\nabla\psi, \nabla \theta)) + \nabla \psi = 0 & \forall x \in \Omega, t \geq 0 \\
\psi(x,y,t = 0) = 0 & x \in \Omega \\
\psi(x,y,t) = 0 & x \in \Gamma_0, t \geq 0 \\
\psi(x,y,t) = +\infty & x \in \Gamma_1, t \geq 0
\end{cases}
$$

The parameter $t$ has no physical meaning, it is only an iteration parameter. The solution of (1,2) must be searched in the class of viscosity solutions.

The computational domain is discretised in 2D with a triangular mesh. We denote by $T$ any current triangle and $M$ any mesh point. The discretisation of (2) is carried out via the scheme:

$$
\begin{align*}
\psi_M^0 &= 0 \\
\psi_M^{n+1} &= \psi_M^n - \Delta t(-R(M) + H(M, p_i^n, \ldots, p_M^n))
\end{align*}
$$

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In (3), H, the numerical hamiltonian, is an approximation of $\|\nabla \psi\|$ known as the Godunov hamiltonian. Its arguments are the gradients of the piecewise linear interpolation of $\psi^n$ on the mesh. The list, $p_i^n, ..., p_iM$, is the list of the gradients for all the triangles having M as vertex. $R(M)$ is an approximation of $\alpha(\nabla \Phi, \nabla \theta)$, it is enough to have an approximation of $\alpha$ which is the average angle at node M. A remarkable point of this algorithm is that the boundary conditions of (2) are automatically contained in the numerical hamiltonian $H$.

The time step $\Delta t$ is computed via the CFL like condition $\frac{\Delta t}{h} \leq 1$ where h is the maximum diameter of the triangles T.

The convergence of this explicit scheme can be improved by using a local time stepping as in CFD.

The shape of the propellant flow organization is deduced from grain filling simulations performed using the SNPE code MONTREAL® in which a segregation model has been integrated, and from NMR imaging visualisations (Figure 8 and Figure 9).

Figure 8: Shape of Flow Organization (Rotating Casting with Mandrel).

Figure 9: Shape of Flow Organization (Rotating Casting without Mandrel).
The MONTREAL® computation code is built around a finite volume technique that solves the Navier-Stokes equations for incompressible fluids. Particular attention was therefore paid to the management of the free surface tracking. Several numerical methods can be used to describe and simulate the free surface of the flow: the LAGRANGIAN method, the particle method, the volume of fluid method (VOF)\textsuperscript{[14,15,16,17,18,19,20,21]}. Specificity of MONTREAL® lies in the description of the free surface of the propellant flow. A first version of the software using an advection equation method had been developed. Some numerical diffusion problems brought about the creation of a new version using a VOF CIAM method. VOF CIAM is also known as the “Piecewise Linear Interface Construction” method (PLIC). It is a step by step reconstruction. The strength of this method lies in the reconstruction of the interface as a function of the orientation. Compared to standard QUICK or TVD methods, VOF CIAM exhibits no numerical diffusion phenomenon. VOF is usually called “a slow algorithm” but recent implementation shows that it is possible to obtain quite the same computation time with VOF CIAM and with QUICK or TVD.

The exploitation of those results gives a periodic organisation made of three layers:

- Layer 1: Propellant over concentrated in ammonium perchlorate (called PA).
- Layer 2: Propellant under concentrated in ammonium perchlorate.
- Layer 3: Mean composition.

Each layer $i$ has a thickness $e_i$, a burning rate $v_i$ and a density $d_i$.

The burning rate value for each layer is adjusted to obtain the best agreement between numerical and experimental results.

4.0 PRESENTATION OF NUMERICAL AND EXPERIMENTAL RESULTS

4.1 Experimental Results

The experimental results are of two types. The first one corresponds to the global behavior of the motor and is represented by the hump effect and the mean burning rate deduced from firing tests exploitation. The second one corresponds to a local behavior and is deduced from local measurements.

Figure 10 shows the evolution of pressure obtained during firing tests for each process. Those curves show that the behavior of the grains is different, at first from a qualitative point of view (hump effect) and then from a quantitative point of view (mean value of burning rate: scale factor).
Table 1 gives the corresponding values of mean burning rate. The ratio between the burning rate obtained for processes A and C and the value measured for process B is also computed. It appears that the grain manufactured using a casting without mandrel has a lower burning rate than the others of about 3%.

Table 1: Mean Values of Burning Rate

<table>
<thead>
<tr>
<th></th>
<th>Process A</th>
<th>Process B</th>
<th>Process C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean burning rate (mm/s)</td>
<td>7.55</td>
<td>7.28</td>
<td>7.48</td>
</tr>
<tr>
<td>Ratio with Process B (Experience)</td>
<td>1.037</td>
<td>1</td>
<td>1.0275</td>
</tr>
<tr>
<td>Ratio with Process B (Simulation)</td>
<td>1.032</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Figure 11 and Figure 15 show the hump effect curves obtained for processes A and B. They are quite different, and the curve obtained for process B is characteristic of grains stamped after casting.

Figure 12, Figure 16 and Figure 19 show the profiles of the radial burning rate along the web for the three processes. This ones are adimensionned profiles, but the ratio between each process is conserved. For the three points casting the profiles under the casting point and in the knit-line are given. Those results are obtained by ultrasonic measurements. We can notice that like the hump effect, the profiles are very dependent on the process. Overall, the radial burning rate profile is directly related to the hump effect. In Figure 13 and Figure 17, the longitudinal burning rate profiles along the height of the grain are presented for processes A and B. In both cases, the profile is quite constant. We will talk more precisely about those results in the next paragraph (comparison of experimental and numerical results).

Concerning more precisely the grain manufactured using a casting mandrel in place (process A and C), the profiles of the radial burning rate along the web are of the same type. We can also notice that concerning the three points casting, we obtain very different profiles under the casting points and in the knit-line. Furthermore, the mean value is 2.2% greater in the knit-line. Those results are in agreement with the observations on large SRM and particularly with the after firing measurements of thermal protection erosion. Indeed, in large SRM manufactured using a three points casting, a stronger erosion of thermal protections of the case along the knit-lines is measured after firing tests.

![Figure 11: Process A – Hump Effect (Firing Test Result).](image)
Figure 12: Process A – Radial Burning Rate along the Web (US Result).

Figure 13: Process A – Longitudinal Burning Rate along the Height (US Result).

Figure 14: Process A – Longitudinal Burning Rate along the Web (Strand Burner Result).

Figure 15: Process B – Hump Effect (Firing Test Result).

Figure 16: Process B – Radial Burning Rate along the Web (US Result).

Figure 17: Process B – Longitudinal Burning Rate along the Height (US Result).
### 4.2 Comparison of Experimental Results with the Numerical Simulation

For processes A and B, numerical results are superimposed to experimental results on the figures mentioned above.

Concerning process A (rotating casting with mandrel), the global behavior of the grain, shown through the hump effect on Figure 11, is well predicted. The local behavior is also well simulated. The curves plotted on the Figure 12 and 13 show that our model is able to predict the shape of the radial burning rate variation along the web, and the longitudinal burning rate variation along the length, and furthermore the ratio between the radial and the longitudinal burning rates (about 2%). The evolution of the longitudinal burning rate along the web is also well predicted as it is presented on Figure 14.

To sum up, in the case of process A, our model is able to predict both global and local behavior of the grain and furthermore the non isotropic behavior of the propellant in accordance with processing.

The comparison, in the case of process B, is more difficult because, as shown by the filling simulation and by the local measurements, the behavior of the grain is different from the bottom to the top and, as stated above, during the simulation, the stratification is supposed to be strictly periodical. Nevertheless, the comparison of computed and measured hump effect curves in Figure 15 shows that the global behavior is well predicted. The agreement is not so good concerning the radial burning rate along the web (Figure 16). This is partially due to the fact that the measurement is obtained using two samples.
Between them, there is an area in which no measurement is available. The problem is that the simulation predicts an increase of burning rate in this area, which is characteristic of this process, that we are able to measure. On the other hand, the comparison presented in Figure 17 and 18 for the longitudinal burning rate is satisfactory. Furthermore, the ratio between the mean radial burning rate and the mean longitudinal burning rate is also well predicted (about 5%).

The comparison of processes is also illustrated in Table 1 through the mean burning rate ratio. The computed value (3.2%) is very close to the measured value (3.5%).

5.0 CONCLUSIONS

The manufacturing process has a great impact on SRM performance. Particularly, the propellant heterogeneity, due to the particle segregation in the propellant during filling, leads to operating particularities like the hump effects and a large part of the scale factor.

An experimental study has been performed on small scale composite propellant grains to quantify the impact of manufacturing processes on ballistic performance. The global performance and the local behavior have been analyzed by means of firing tests and local measurements. The important influence of the manufacturing process on both global and local behavior has been clearly demonstrated.

The experimental results have been compared to the simulation results obtained using a new code developed at SNPE to compute surface burnback in composite propellant. The input values necessary for the simulation have been deduced from filling simulation and NMR visualization. The experimental and numerical results are in very good agreement.

This paper only raises the two-dimensional results. Indeed, in order to validate our model on industrial configurations (Complex geometry or manufacturing process), the three-dimensional version of our code is used. The results we have obtained on large grains are promising. For instance, the simulation of the three points cast grain has been performed. The model is able to simulate the whole behavior of the grain. It was also able to simulate the radial and the longitudinal burning rate profiles along the web (under a casting point and a knit-line plane).

Now, our objective is to compute the performance of large scale motor manufactured using complex filling process in order to integrate in the simulation, effects usually integrated in hump effect and scale factor. The problem of the classical method is that it requires preliminary firing tests results. This model gives significant improvements of ballistic prediction. This new method will particularly enable us to predict the performance of a SRM in the case of an anomalous filling and then help to decide if the segment may be used for flight or not. It will of course also enable us to predict the performance of a new motor, before the first firing test and taking into account the casting process.

6.0 ACKNOWLEDGMENT

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7.0 REFERENCES


