Formulation of a mechanically improved paraffin fuel

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Abstract
This paper wish to browse mechanical requirements, solid fuel formulation and casting process in order to produce high efficiency and high reliability aluminized paraffin wax grains for hybrid rocket propulsion. By the means of finite elements simulation, the grain mechanical integrity during motor operation and the grain thermal transient during casting are studied, giving specifications in terms of maximal strain and maximal thermal flux, in order to prevent cracks during all the grain life cycle. Different blends of waxes are mechanically characterised, and an affordable and repeatable way to cast any kind of large scale grain is developed.

1. Introduction

In this first part we present the general way how an hybrid rocket motor does work, and how hybrid propulsion could reach a sufficient Technology Readiness Level to compete current solid and liquid solutions.

1.1 Hybrid rocket motor basics

An hybrid rocket motor has the major characteristic to separate both fuel (as a solid stored in the combustion chamber, like solid propulsion) and oxidizer (as a liquid or a gas stored in a pressurized tank, like liquid propulsion). This is a strong advantage towards grain fabrication and handling (no pyrotechnic reaction possible), and motor operation (start / stop capability with only one fluid line to control).

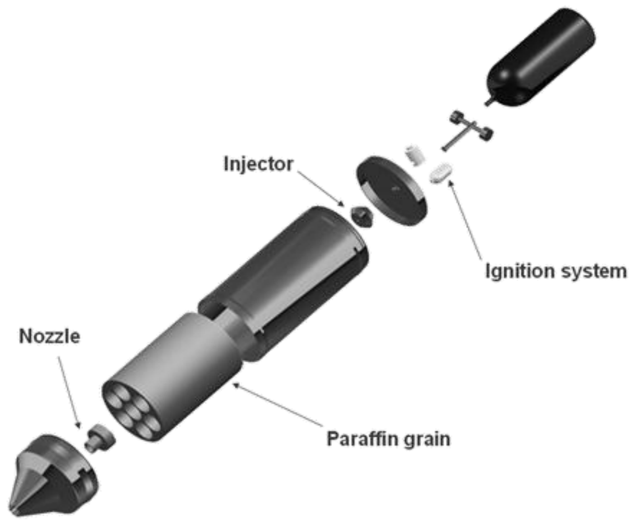

Figure 1: Design of an hybrid rocket motor

This also explains why all around the world engineering schools are successfully involved in improvements of this technology [3, 4, 6, 7].

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1.2 Challenges to meet

Due to high development costs of conventional propulsion systems and launchers, space access had ever been limited to some multinational companies and state institutions. Therefore, since numerous private (SpaceX, SpaceDev, Scaled Composites, Armadillo Aerospace, Xcor Aerospace …) and academic (Stanford, Purdue, Kyushu …) initiatives recently appears on the suborbital flight or nanosatellite launch market, hybrid propulsion is seriously considered carried by its safety and low cost operability.

This propulsion concept needs however to overcome problems as low frequency instabilities and poor combustion efficiency [2, 8]. At the time of writing, lots of works have already proved that increasing regression rate of the fuel grain is the key of stable and efficient rocket motor designs [4]. This can be achieved using liquefying fuel: during combustion, a thin and hydrodynamically unstable liquid layer is formed above solid fuel surface and small droplets are dragged away in oxidizer flow, increasing effective heat-exchange surface and mass transfer [1, 3].

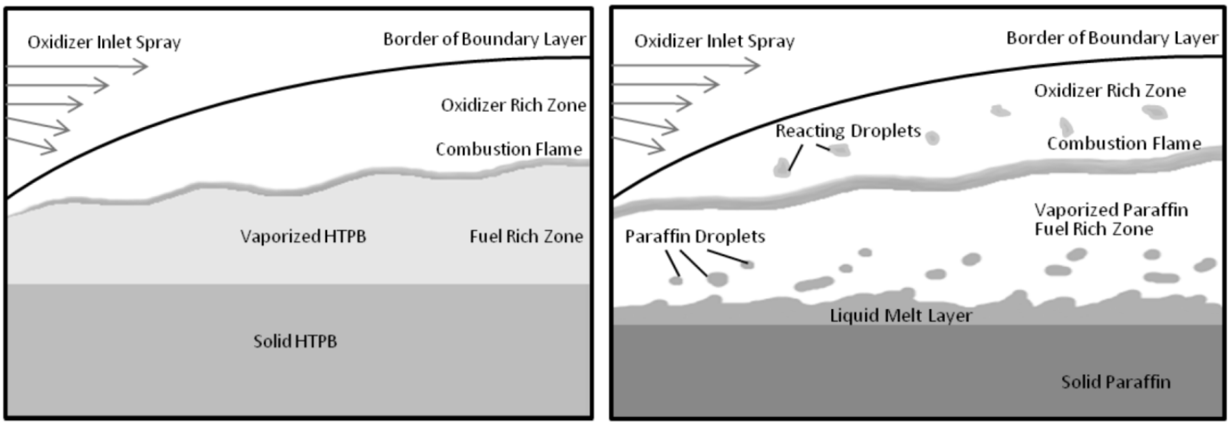


Figure 2: Left, low regression rate hybrid - Right, high regression rate hybrid [7]

But liquefying fuels, as waxes paraffin, do not have proper mechanical properties [5, 6] that allow the grain to withstand the launch's stress loads (acceleration combined to pressurization and radial expansion of the combustion chamber). Moreover, instead of polymerized materials as solid propellant, such thermoplastic materials exhibit strong density variations between liquid and solid phase. This makes fabrication process a real challenge.

2. How to prevent the grain failure during casting

No reasonable application will be possible until a comprehensive fabrication process has been developed. Its specifications would be:

- Repeatable and reproducible
- Allowing large and small scale grain
- Allowing any kind of waxes, additives, metallic powders
- Allowing any kind of port shape
- No machining grain required
- No shrinkage, no cracks, no voids observed

This part presents our efforts to understand how to cast heterogeneous fuels composed of micrometric aluminium powder and waxes blends.

2.1 Design of a casting process

In this study, the grain is a ring shaped object that is 500mm high and 55mm thick, the port diameter (i.e. the combustion chamber) is 40mm.

Paraffin wax melts at low temperatures between 50°C (122°F) and 85°C (185°F). Those temperature levels enable easy manipulations in order to obtain a large variety of grain geometry. However, paraffin wax is a thermoplastic that exhibits a strong shrinkage (10 to 20%) when turning from liquid to solid phase. This mass density change leads to grain deformations and internal stress.

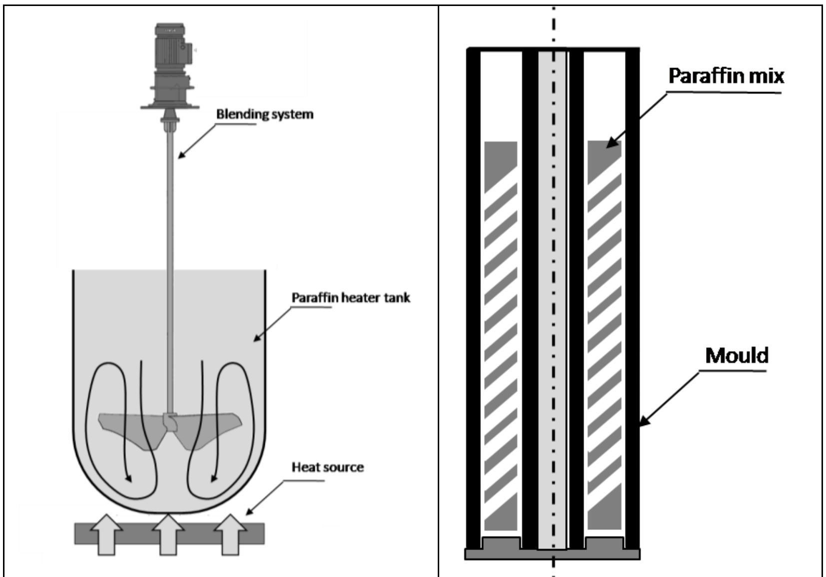
To reach highly energetic combustion, the grain is composed by 25% of aluminium powder and 75% of waxes blend. The aluminium powder is added to liquid paraffin which has high wetting properties. Liquid paraffin is especially fluid with low viscosity levels (about 0,05Pa.s). This property is actually a major issue: the low viscosity cannot prevent the aluminium from falling by gravity, which gives, if noting is done, a two phase material. A problem that remains even with fewer aluminium particle diameters (10µm):

Figure 3: Sample for which aluminium fall significantly

In fact, we have to deal with three technical challenges:

- Paraffin’s physical characteristics impose to deeply study the thermo-mechanical behaviour of the grain during casting operations.
- The process must handle the mixing of aluminium powder with liquid paraffin in order to obtain a stable and homogenous blend.
- Because the homogenous state is difficult to reach and keep (the temperature is falling), the grain must be made as fast as possible.

Considering those points, a casting process is selected. Paraffin and additives are heated and melted in a tank, homogenized, then poured into a mould made of two aluminium cylinders.



Melting and homogenization device	Mould

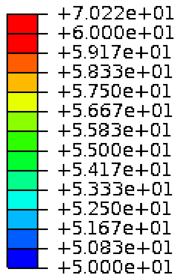
Figure 4: Selected casting process

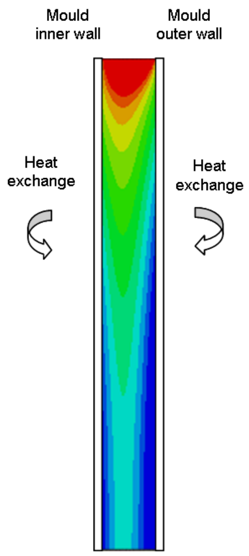
Using a mould allows casting all the grain in one fast operation with low cost equipment. Moreover, this method permits large scale grain casting without major process evolutions. Works on the process described below are meant to master those three points.

2.2 Experimental highlights of grain failure during casting

Before being able to cast sophisticated blends, our works focused on pure paraffin behaviours. Unexpectedly, this case is the most difficult one to solve. Paraffin shrinkage during phase change (density changes between liquid and solid states) is obviously highly studied in a casting process. But paraffin shows stranger behaviours than just shrinkage: cavities, cracks and internal rips appear even though the outside grain seems good after unmolding.

Finite elements simulation is used to understand the mechanisms that lead to such geometrical defects. Thermal transient is solved in grain and mould. The mould's walls are exchanging heat with the ambient air.



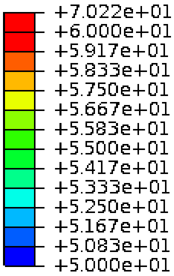


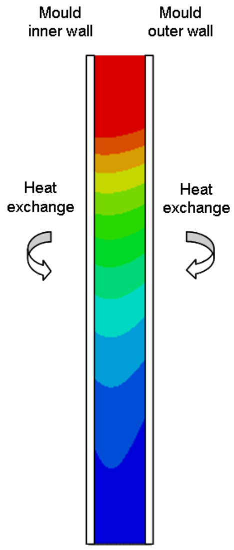
Temperature (°C)	Wax with nominal thermal conductivity (0,2 w.m^{-1}.K^{-1})	Grain after unmolding

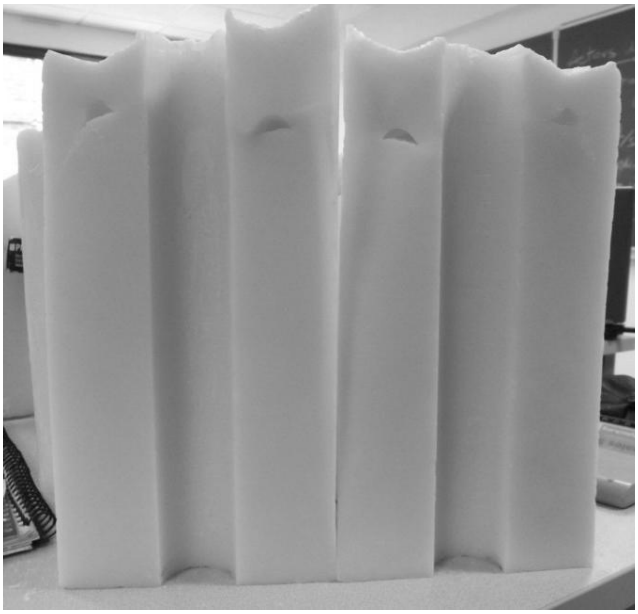
Figure 5: Highlights on radial gradient influence

As presented above, simulation clearly shows that if cooling is not homogeneous and starts from the inner and outer walls, an annular crack will appear.

On the contrary, figure 6, we can see that when the cooling is homogeneous (because of insulation or because thermal conductivity of the fuel is increased) the grain is quite perfect.







Temperature (°C)	Wax with high thermal conductivity (2,0 $w.m^{-1}.K^{-1}$)	grain after unmolding

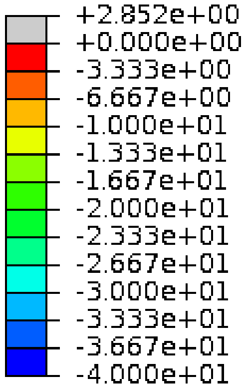
Figure 6: Highlights on radial gradient influence

Therefore, the mould must prevent, thanks to its design, high thermal gradient in the grain core. The cooling process must be slowed down thanks to thermal insulation walls. A heating cover, with thermal control, is added to the metallic mould. Then, only the top (air) and bottom of the mould allow the grain to cool off.

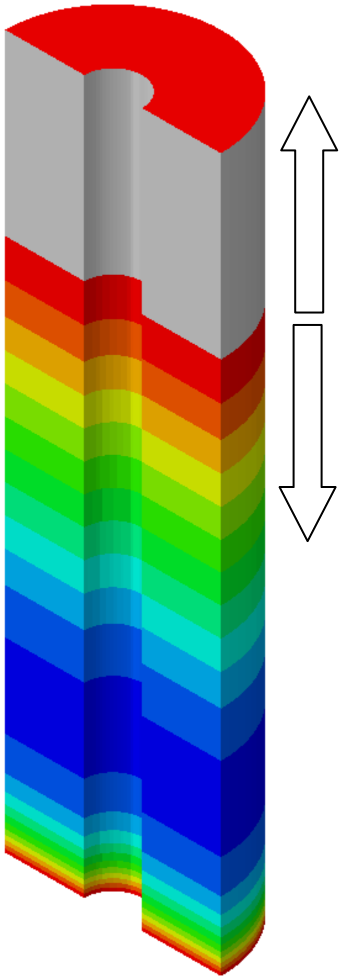
After some convincing results for reduce scale grains (300 mm high) as mentioned figure 6, further tests have been made with 600 mm high grains. The wish to avoid thermal gradients is still present. With a decrease of -5°C (-9°F) per hour, thermal fluxes from the heating cover are controlled by the temperature measurement. The cover is turned off after the heat level pass under solidification state of the paraffin. The result can be seen on figure 7 below.

With this result, we confirm that there is no more radial thermal gradient because there is no cavity in the grain's core. But a hole is visible, separating the grain into two parts by the middle.

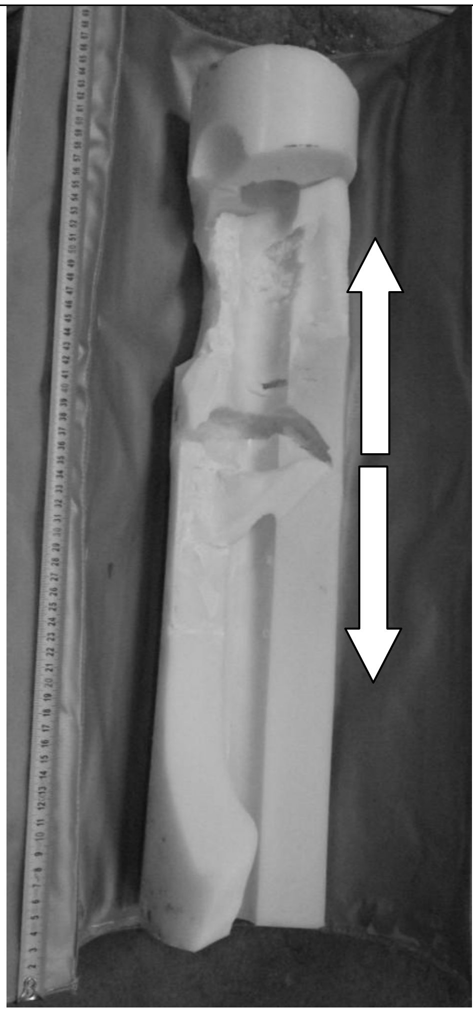
The finite elements simulation can explain the paraffin behaviour: the material increase in density (shrinks) from the coolest zone first to the last hot zone. Because the mould has two cold faces (i.e. with no heat control) that are both mould's top and bottom, the shrinkage is working in two opposite directions at the same time. Thus, the location where those opposite movements meet will be the crack.



Displacements (mm)



Displacements (mm)
Positive displacements are in grey



grain after unmolding

Figure 7: Highlights on longitudinal gradient influence

Works on casting pure paraffin are still in progress. The process study currently focuses on means to have a longitudinal thermal gradient in one direction only, by also insulating the top the grain. Nevertheless, concurrent works have been made on aluminized paraffin grains. Results are detailed below.

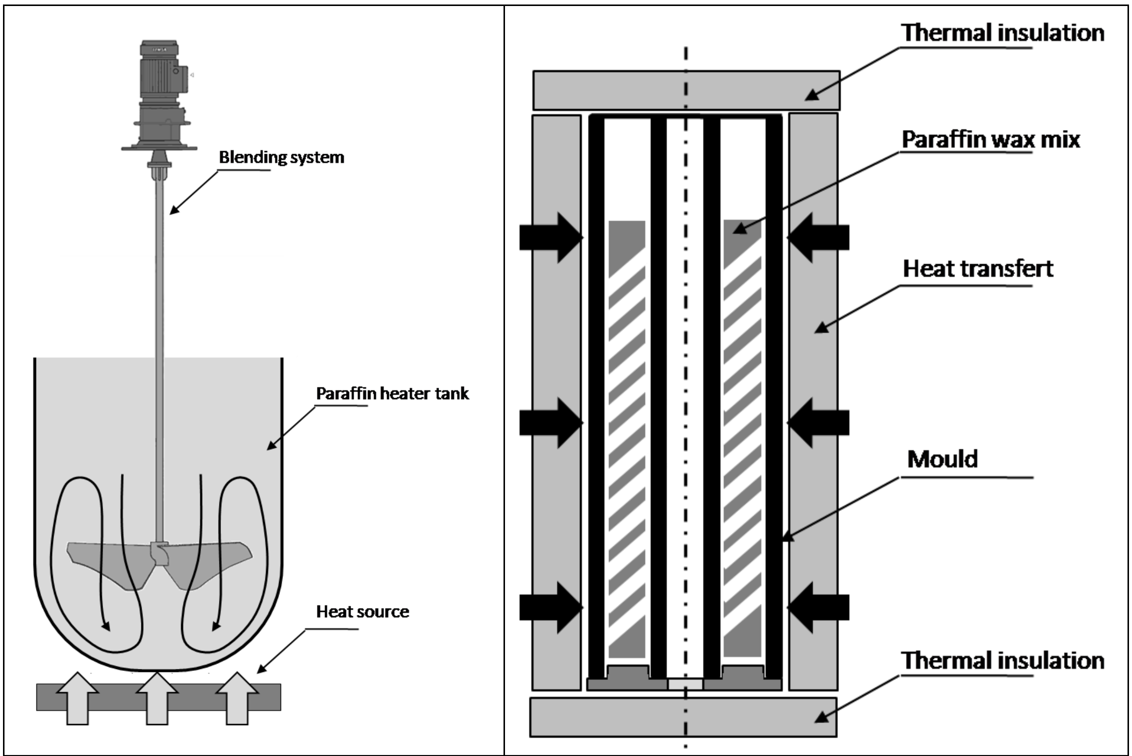
2.3 Micro-sized aluminium powder handling

In order to obtain and homogenous mix between liquid paraffin and aluminium powder, aluminium particles are added to paraffin when the first one is liquid.

Micro-sized aluminium particles handling can be dangerous: breathing heavy particles is obviously unhealthy but worse, aluminium particle can spread in air and might ignite a deflagration if there is flame or static electricity. In order to avoid these hazards, the aluminium powder is kept in a glove box. Before to take it out and to mix it with paraffin, the powder is aggregated with mineral oil (oil can also be used in order to change paraffin mechanical properties) and a paste like material is obtained. This paste can be dissolved in hot paraffin.

A blending system is used in order to keep aluminium particles in suspension while the paraffin progressively cools off. Because paraffin viscosity raise during the temperature drops, the mixing operation ends when aluminium powder does not fall anymore.

Usually, this state of high viscosity is obtained around 5 degrees over the solidification point. Afterwards, the blend is quickly poured in the mould were it solidifies.



Melting and homogenization device	Insulated mould

Figure 8: Retained casting process

In fact, the blending system brings another advantage: by mixing paraffin, it allows to have a homogenous liquid paraffin temperature. If the paraffin is not blended, a solid skin appears on its top surface. By mixing, we ensure that this cold layer return in the hot liquid. Thank to this system, the paraffin is cooled off near its solidification point, and because the casting temperature is lower, thermal gradients are weaker. Therefore, the blending system is also used before casting pure paraffin.

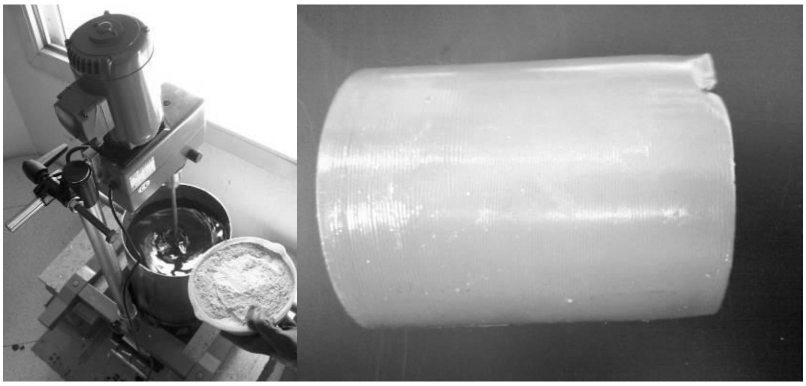


Figure 9: Process in operation and aluminized grain obtained

Aluminized paraffin grain can be obtained without any defect with this exact casting process. Aluminium also helps to avoid cavities, cracks and other irregularities. The reason is quite simple: by adding aluminium, the thermal conductivity of the paraffin is levelled up and temperature is quite homogeneous in all grain.

3. How to prevent the grain failure during motor operation

Launcher's mission can only succeed if thrust, so surface in combustion, is known and consistent with nominal operation.

This is not the case in hybrid propulsion because regression rate is not homogeneous all along the port, but worse, because the grain's mechanical integrity is not ensured. To avoid grain failure, combustion surface increase, and unburned fuel blocking nozzle throat, a mechanical characterization and mechanical specifications (in terms of strain at failure) are needed

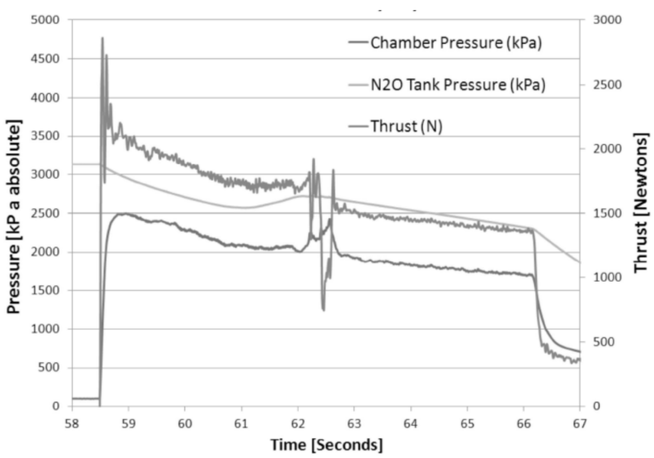


Figure 10: Effect of grain failure during the motor operation (see between time = 62s and 63s) [6]

This part presents our efforts to develop a blend of waxes that will satisfy mechanical loads of a launch.

3.1 Grain mechanical behaviour during motor operation, finite elements simulations

Because no mechanical requirement exists to ensure the grain mechanical integrity during the motor operation, finite elements calculations are used to produced them: considering linear elasticity and incompressible response of the fuel (small deformations, no plasticity and no damage) and considering that launch is well represented by acceleration and pressure loads, the maximum stress obtained in the mesh gives us the yield strength paraffin wax needs to not break.

Figure below show our grain design cased in a 2 mm shell of aluminium that can expanse under combustion products pressurization. The higher deformations are always observed at the middle of the grain, on the port skin.

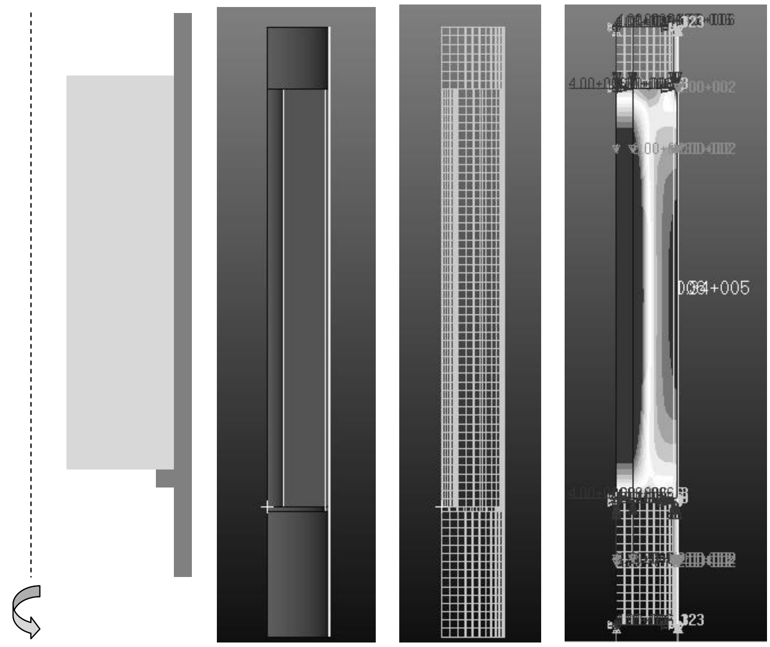


Figure 11: Sketch, design, mesh and map of Von Mises Stress

Of course, deformation depends on mechanical strengths of both shell and grain. We can see below how a rigid shell reduces grain expansion, i.e. grain failure. But to limit inert mass and to avoid grain failure, the formulated fuel has to hold above the dotted curve.

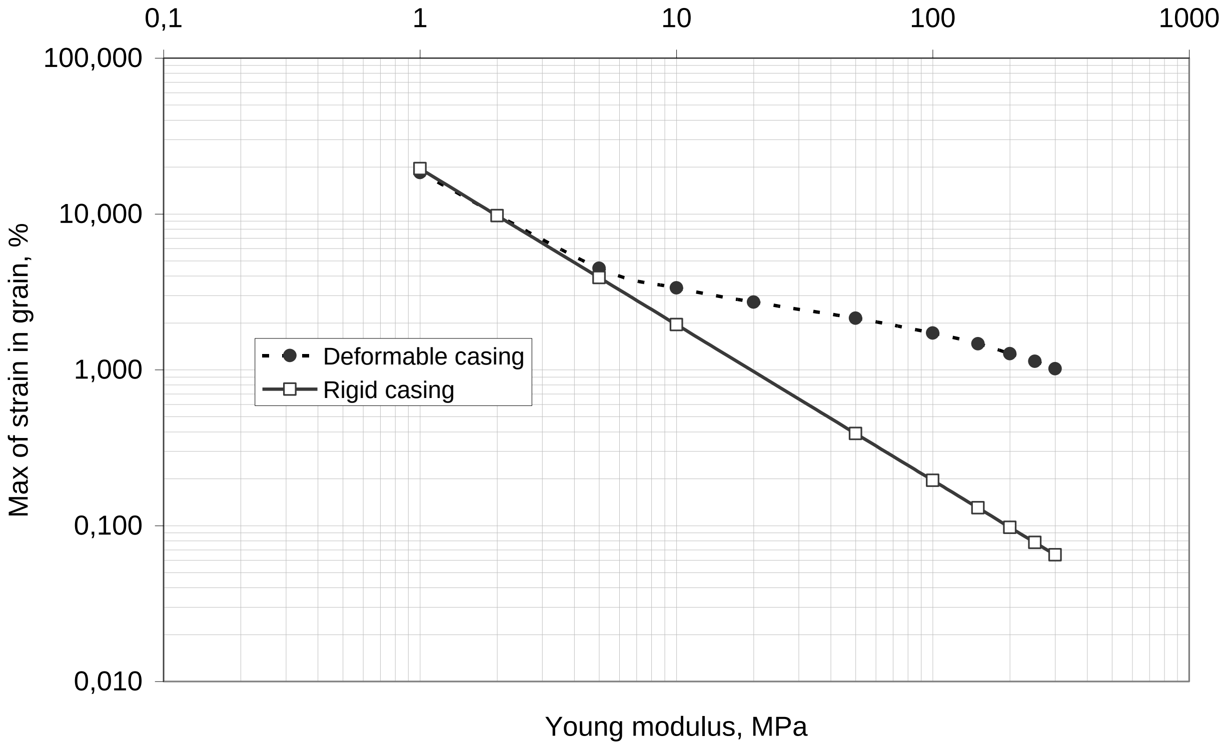


Figure 12: Max of strain in grain depends on shell and grain mechanical strengths

3.1 Mechanical characterisation of wax blends

To improve mechanical properties of our fuel, four additive families can be explored:

- Synthetic and vegetal fibers
- Polyethylene waxes [1, 4]
- Microcrystalline waxes
- Organic acids

At the time of writing, three blends of waxes were tested and compared to pure paraffin wax in order to select those satisfying both mechanical criterion and entrainment capability, as illustrated in [4]:

Blend #1 contains paraffin and microcrystalline waxes and mineral oil.
Blend #2 contains paraffin and synthetic fibers.
Blend #3 contains paraffin, microcrystalline and polyethylene waxes.

Mechanical properties as Young modulus (taken on linear part of the curve) and ultimate strength (defined as F_{max}/S_o) are obtained from uniaxial compression tests. Samples are cylinders of length / diameter ratio > 2,50 (to avoid multiaxial effects).

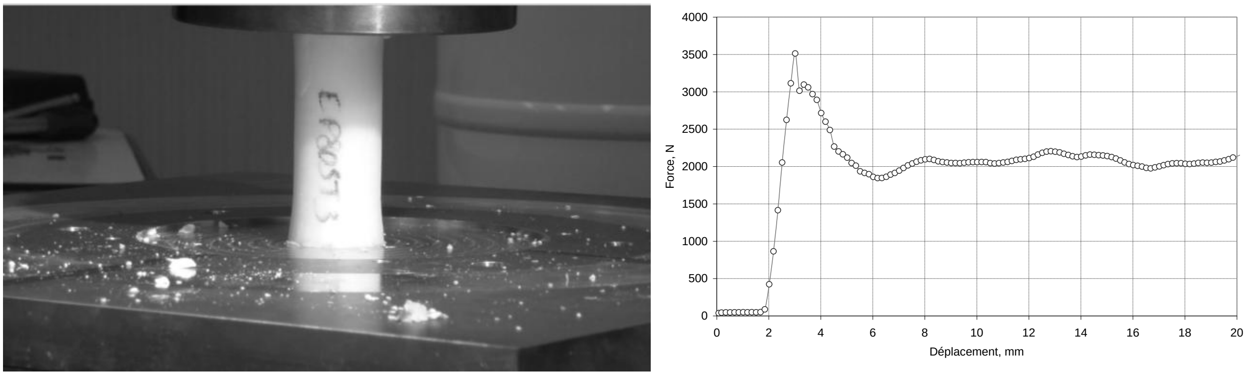


Figure 13: Uniaxiale compression test and sensors data

Results are reported in figures below. It can be noted that all formulation characterized satisfies the criterion when the web thickness is maximal (at the beginning of motor operation).

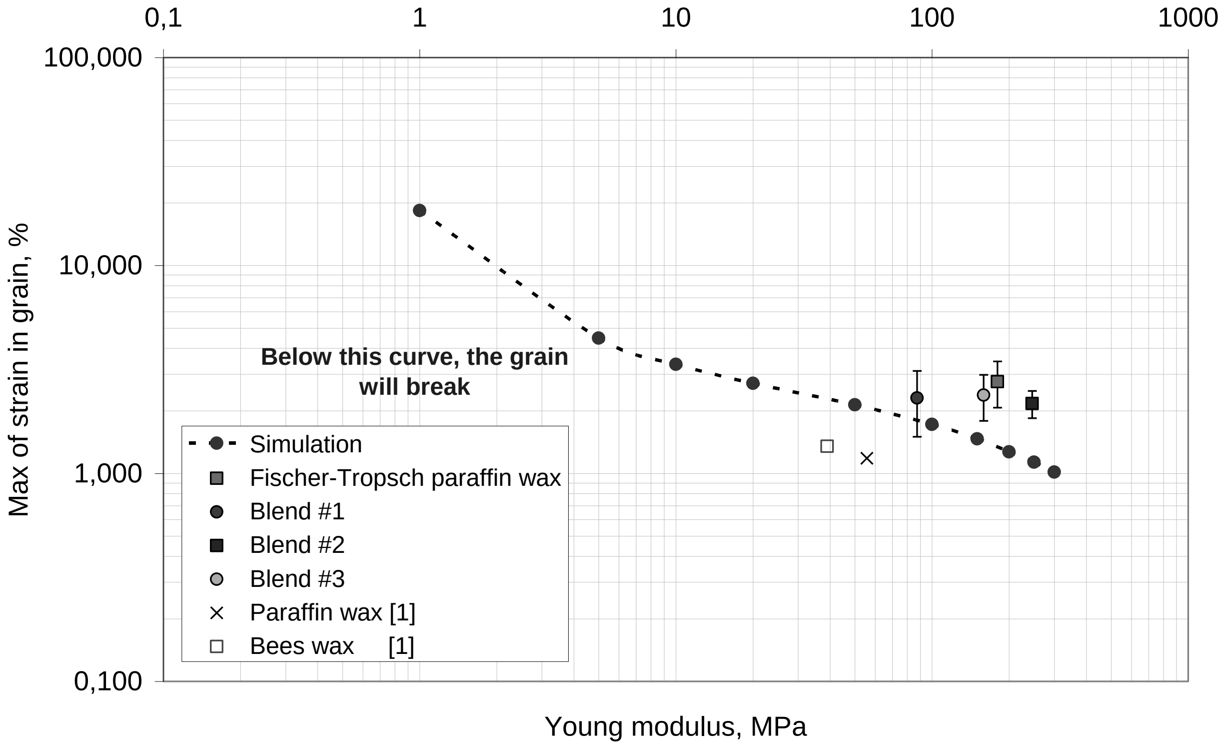


Figure 14: Comparison between material properties and requirements

During operation, the web thickness decreases and grain's deformations increase. According to figure below, all our fuels would have broken before combustion ends.

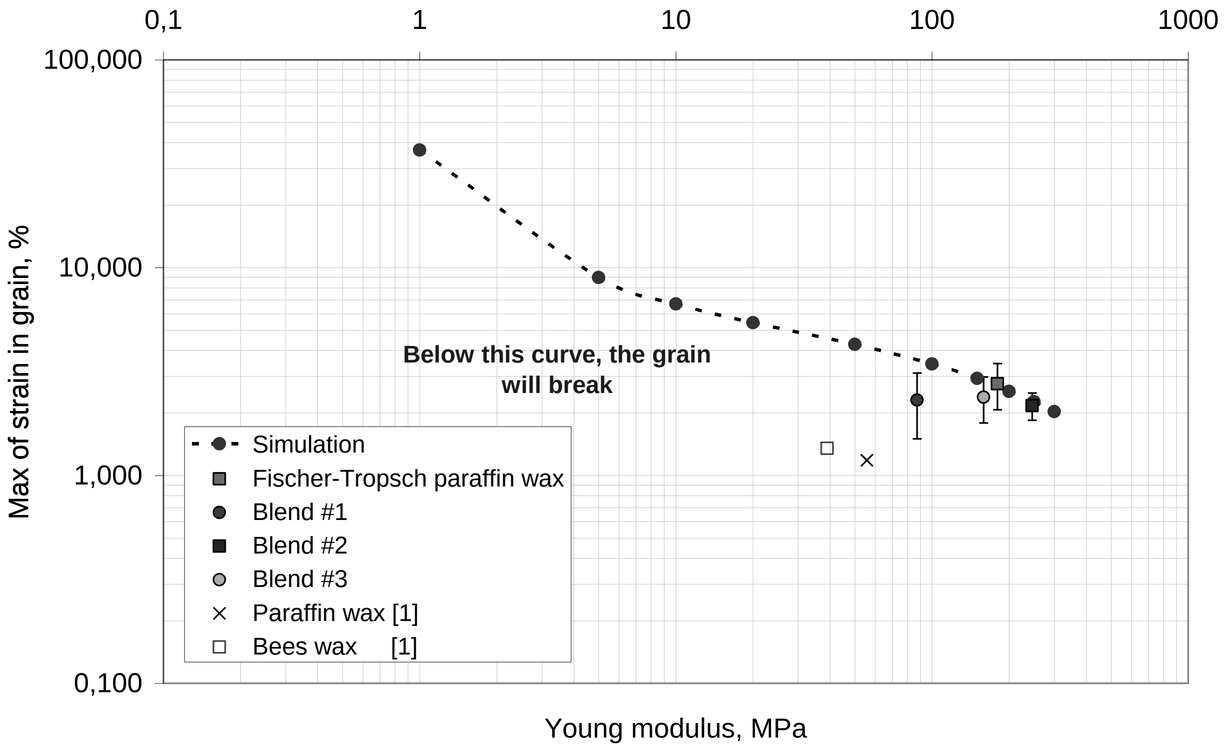


Figure 15: Comparison between material properties and requirements

4. Conclusion

Our works focused on the way to avoid hybrid rocket grain fuel failure during all its life cycle, and more particularly casting and motor operation.

A casting process allowing any kind of waxes, additives, port shape end grain length has been designed and tested. Numerical simulations and numerous experiments clearly show that uncontrolled temperature gradients in the grain are responsible for geometrical defects.

An improved process is proposed, in which waxes and additives are blended till to obtain a low temperature / high viscosity material (lowering shrinkage) then poured in an insulated mould. By this way, aluminized grains satisfy all geometrical requirements.

Finite elements simulations are also conducted to determine the loads that grain has to accept during motor operation. More than 2% of strain is reached in port, depending on the fuel’s strength on the web’s thickness. Different blends and pure materials are characterized and compared to mechanical requirements. Blends made with synthetic fibers and polyethylene waxes are promising fuels for high efficiency hybrid rockets.

Elisa Aerospace Engineering School is very thankful to its financial and technical supports: Cnes, Onera, Planète Sciences, AJSEP, IUT Bordeaux I and IUT Saint-Quentin.

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