Boosting Hybrid Propulsion by 3D-printing: the Armored Grain and its Performance Enhancement

__Christian Paravan__, Federico Giambelli, Carlo Rontini, Francesco Calabrò, Davide Tamiozzo, and Letizia Calò
Politecnico di Milano, Aerospace Science and Technology Dept., 34, via LaMasa, 20156, Milan, Italy

The *armored grain* is a heterogeneous fuel formulation for hybrid rocket engines: a 3D-printed structure is embedded in a paraffin-based matrix. The armored grain offers enhanced mechanical and burning performance over conventional paraffin and paraffin-based blended fuels [1,2]. In the blends, a strengthening polymer (typically, a thermoplastic) is added to the wax, with a load in the range 5 to 15 wt.%. Yet, blending inherently reduces the solid fuel regression rate due to the increase in melt fuel viscosity that suppresses the entrainment mass transfer [3]. While metal additives can be used to partially recover the regression rate loss, the impacts of powders with different dispersity are not detailed in the literature. Similarly, for armored grains there is a lack of investigations dealing with (*i*) the effect of the reinforcing structure, (*ii*) the composition of the paraffin-based matrix (in particular, on the possible effects of energetic fillers).

In this work, some of literature open points are tackled. First, different 3D-printed structures (straight and twisted honeycombs, gyroids) are contrasted. At this stage, a macro-crystalline paraffin is considered with a polylactic acid (PLA) as printing material. Then, the gyroid is selected (based on mechanical and ballistic results) as the reinforcing structure to be investigated in a more comprehensive way. This phase of the analysis includes (*i*) testing armored grains with different compositions of the paraffin-based matrix (where a micro-crystalline wax is considered) and acrylonitrile butadiene styrene (ABS) is used to print the reinforcing structure, and (*ii*) testing armored grain formulations loaded with micron- (30 μm) and nano-sized (100 nm) Al powders. Finally, the armored grain is scaled-up from a lab-scale engine to a 400 N hybrid rocket used for static firings.

Experimental results show how the effects of energetic fillers are typically limited in non-armored fuel blends. Focusing on nano-sized Al, at the average oxidizer mass flux (G_{ox}) of 50 kg/(m^{2}s) the percent regression rate enhancement over the non-metallized counterpart spans from 5% (pure paraffin) to 35.9% (paraffin blended with 15 wt% of reinforcing polymer). Yet, under the investigated conditions, the performance enhancement from the metal filler does not cover the regression rate loss caused by the blending. On the other hand, for G_{ox} = 50 kg/(m^{2}s) armored grains with a pure paraffin matrix show regression rate enhancements up to 90% over the non-armored counterpart. Interestingly, for G_{ox} = 45 kg/(m^{2}s) unblended wax-based armored grains loaded with nano-sized Al exhibited a +30% regression rate increase over the non-loaded counterpart. In conclusion, gyroid-embedding armored grains combine fuel mechanical integrity with ballistic performance, an attractive result for advanced hybrid propulsion applications, while nano-Al enables additional tuning but with diminishing returns in viscous matrices. The 400 N firings confirmed stable combustion and scalability of the armored grain concept.

References

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