3D-printing for Hybrid Propulsion: 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

Paraffin-based fuels offer attractive regression rate performance, disclosing the possibility of exploiting hybrid rocket propulsion also in high thrust systems. Yet, the use of paraffin-based compositions requires improvement of their mechanical properties. Two different reinforcing strategies are investigated in the paper: (i) the wax blending with a reinforcing polymer [1] and (ii) the use of a 3D-printed reinforcing structure embedded in the solid fuel grain [2,3]. Fuel grains embedding the 3D-printed structures are called *armored grains*. This study is the first systematic comparison under identical conditions of wax blends vs. armored grains that includes an investigation of the effects of metal additives and a scale-up to the 400 N-class.

Blending the wax with thermoplastic/thermosetting polymers provides mechanical properties reinforcement with detrimental effects on the ballistic response of the strengthened formulations. Such a result is due to the viscosity enhancement of the melted fuel that limits the entrainment mass transfer. Metal additives are a possible solution to mitigate this effect. Metal particle combustion increases the heat feedback from the flame zone to the regressing fuel grain. Yet, the use of energetic fillers has an impact on the overall grain characteristics, in particular on melt fuel viscosity. Embedding reinforcing structures in fuel matrices enhances the mechanical properties without affecting melt fuel rheology. Thus, this reinforcing strategy offers new perspectives toward fuels with a suitable set of mechanical and ballistic properties. The gyroid, a cellular structure with open cells and rapidly printable by fused deposition modeling, is a promising candidate for the use for mechanical reinforcement purposes.

In the study, blends feature a strengthening polymer load in the range 5 to 15 wt.%. Fuels embedding gyroids differ for the infill (i.e., relative density of the 3D-printed part). The impacts of metal additives are investigated at small scale for both blends and armored grains: micron- (30 μm) and nano-sized (100 nm) Al powders are contrasted to evaluate the impacts of filler specific surface area, active metal content, and reactivity. Metal mass fraction load is limited to 10 wt.%. Pre-burning analyses include (i) thermal behavior investigation by differential thermal analysis (DTA)/differential scanning calorimetry (DSC)-thermogravimetry (TG), (ii) rheological analyses and (iii) compression tests. The relative grading of the fuels is performed by combustion tests performed on a lab-scale hybrid rocket engine, with the regression rate as the main observable of interest. Tests are conducted in oxygen and nitrous oxide. Different oxidizer injection schemes (standard and swirl) are implemented. The detailed analysis at small scale is followed by a scale-up of the armored grain to a hybrid rocket engine realized by the Skyward Experimental Rocketry Student's Association of Politecnico di Milano.

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. Concluding, 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

[1] K. Veale, S. Adali, J. Pitot, and M. Brooks, "A review of the performance and structural considerations of paraffin wax hybrid rocket fuels with additives," Acta Astronautica, vol. 141, Oct. 2017, doi: 10.1016/j.actaastro.2017.10.012.

[2] R. Bisin, C. Paravan, S. Alberti, and L. Galfetti, "A new strategy for the reinforcement of paraffin-based fuels based on cellular structures: The armored grain — Mechanical characterization," *Acta Astronautica*, vol. 176, pp. 494–509, Nov. 2020, doi: 10.1016/j.actaastro.2020.07.003.

[3] R. Bisin and C. Paravan, "A new strategy for the reinforcement of paraffin-based fuels based on cellular structures: The armored grain — Ballistic characterization," *Acta Astronautica*, vol. 206, pp. 284-298, Feb. 2023, doi: 10.1016/j.actaastro.2023.02.027.