Additive Manufacturing of Corrosion Resistant UHTC Materials for Chloride Salt-to-sCO_2 Brayton Cycle Heat Exchangers

DOE Summit on Gen3 Concentrating Solar Power Technologies

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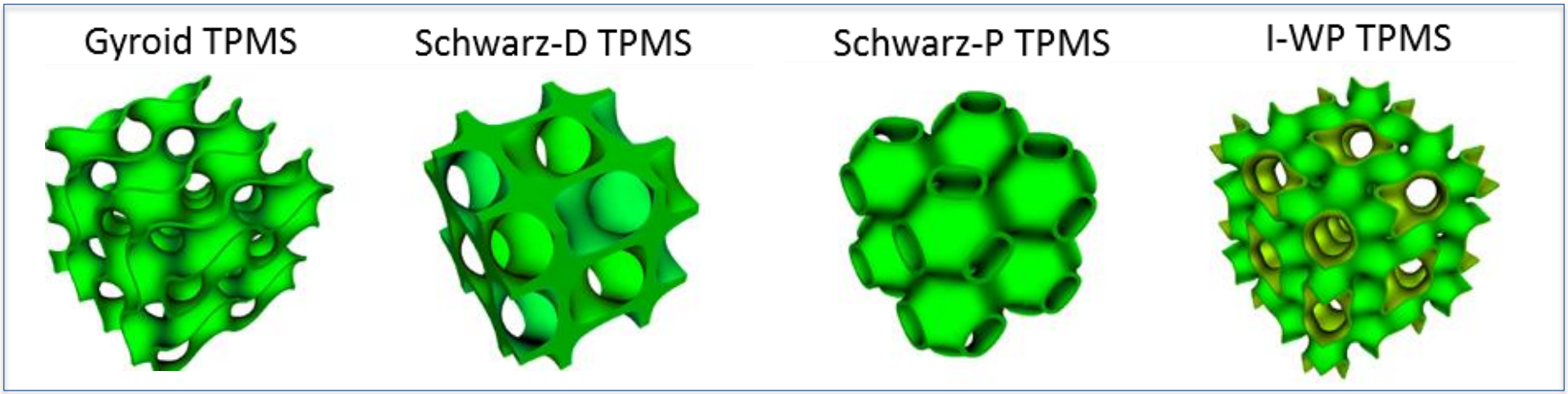
Advanced Designs, Materials, and Manufacturing

- Heat Exchanger Design
  - Triply periodic minimal surfaces
  - Graded structures
- Materials
  - Ultra-high temperature ceramic materials
  - Analytical screening and molten salt corrosion testing
- Manufacturing
  - Binder-jet additive manufacturing
  - Sintering development

Triply Periodic Minimal Surface (TPMS)

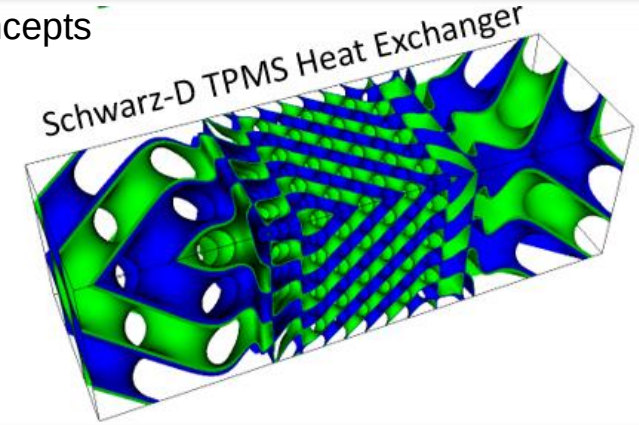


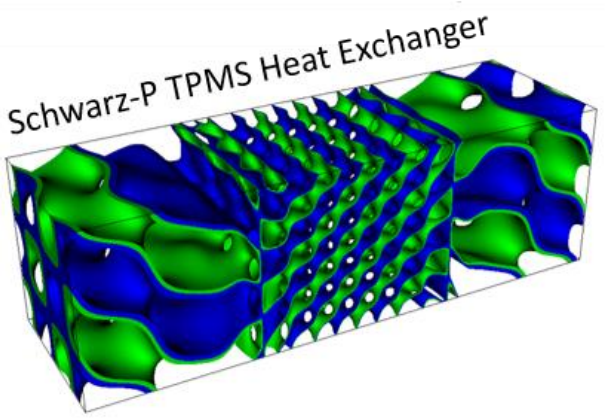
- **Minimal surfaces** - mathematical functions with locally minimized area or zero mean curvature
- **TPMS** – special minimal surfaces with two interpenetrating volume domains extending in 3D
- Femmer *et. al.* (2015) reported on TPMS heat exchanger prototypes with enhanced performance

Calculations for one HX design suggests a power density of 20-50 MW/m^3 (200-1000 MW/kg)

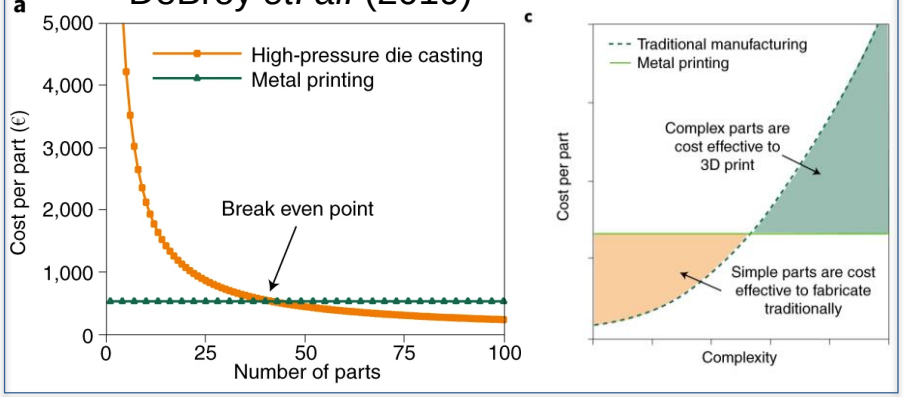
Graded TPMS Structures

LLNL concepts

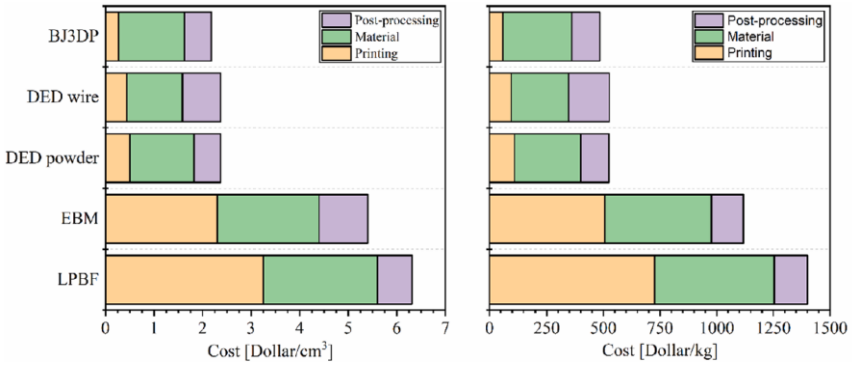




DeBroy *et. al.* (2019)



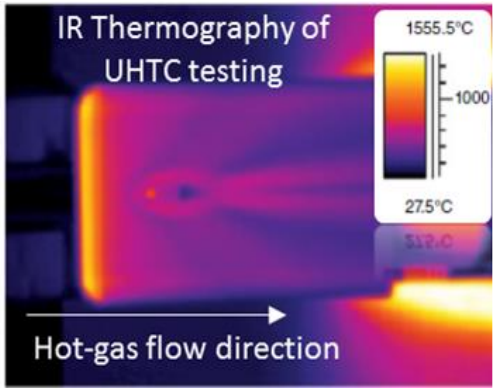
Mostafaei *et. al.* (2021)

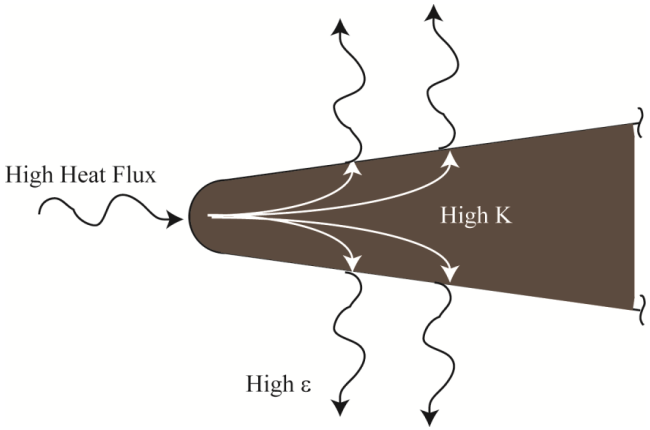


Additive manufacturing is suited to low-volume, specialty, complex products

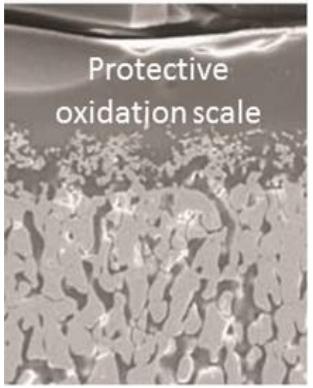
Ultra-High-Temperature Ceramic (UHTC) Materials

Alfano *et. al.* (2014)

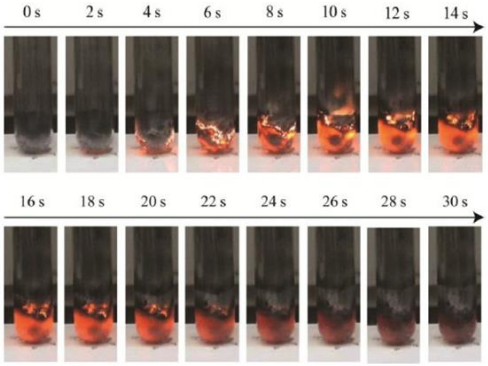


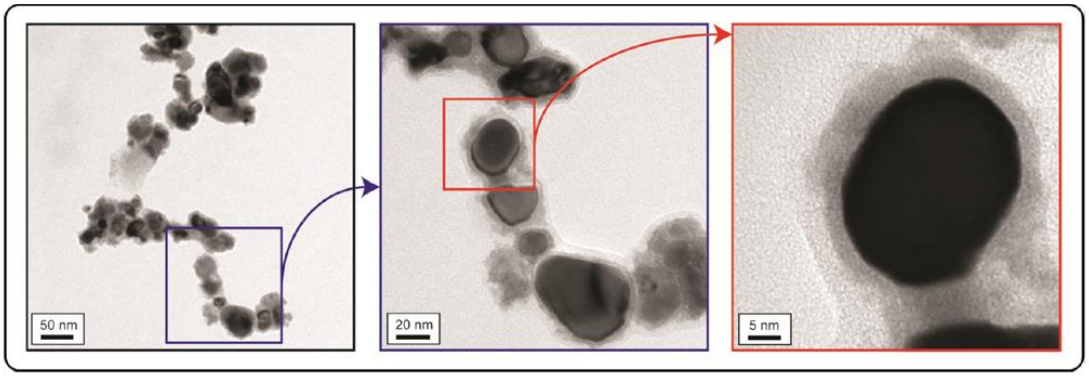


Levine *et. al.* (2002)



Kelly (2013)





Thermal management concepts and molten salt synthesis suggest potential as CSP Hx

Analytical Screening and Molten Salt Corrosion Testing

Analytical Screening

- 36 materials evaluated (Group 4-6 borides, carbides, nitrides, silicides)
- Down selected 9 materials based on a FOM that accounts for thermodynamic, processing, property, and cost factors

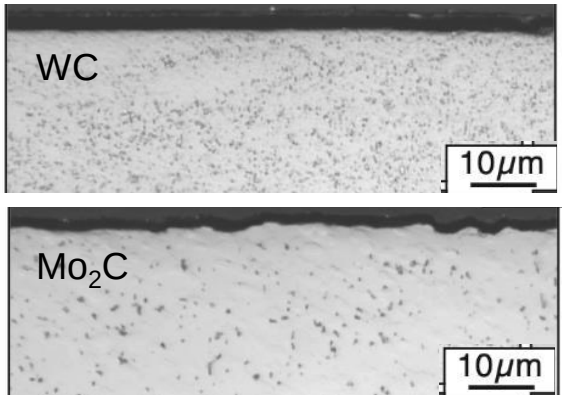
Ni Crucible Testing

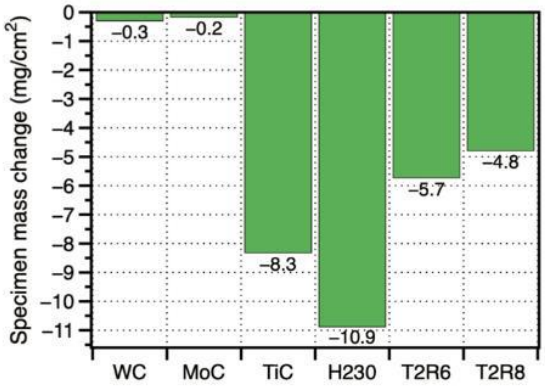
- 9 materials tested in purified KCl-$MgCl_2$ at 800ºC for 100 hours
- Down selected to 3 materials
- Tested in purified salt spiked with H_2O

Mo Capsule Testing

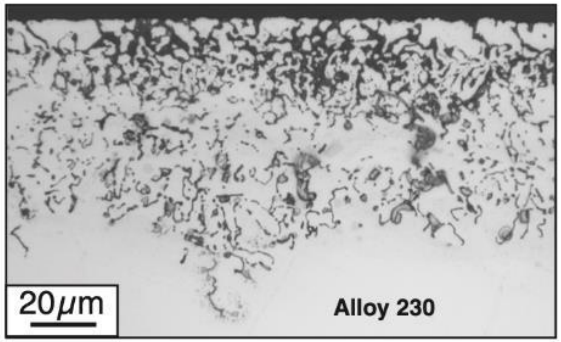
- Repeat tests in sealed Mo capsules using well-established ORNL protocols established over decades of corrosion science experience

No visible attack compared to bulk





Significant attack compared to bulk



Molten salt corrosion resistance of WC and Mo_2C stand out from many materials

Binder-Jet Additive Manufacturing

Raw materials for null candidate

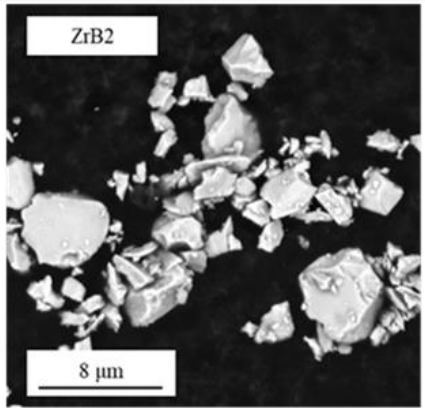
- Evaluated 20 grades of ZrB_2 from 14 suppliers and 19 grades of $MoSi_2$ from 14 suppliers
- Selected 3 ZrB_2 grades
- Selected 3 $MoSi_2$ grades

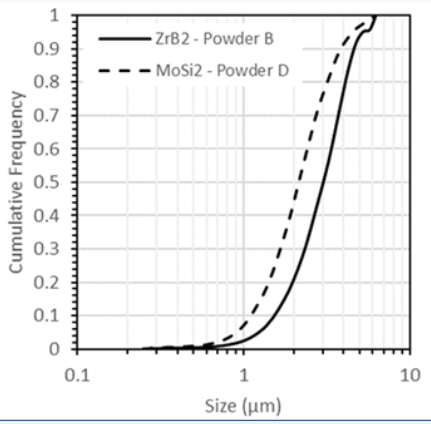
Raw materials evaluations and blending

- Evaluated particle morphology, PSD, and powder rheology
- Down selected to 1 ZrB_2 grade
- Down selected to 1 $MoSi_2$ grade

Printing trials

- Binder compatibility tests
- Developed basic print parameters
- Printed sintering pucks
- Printed TPMS cells with 2, 3, and 4 mm wall thickness

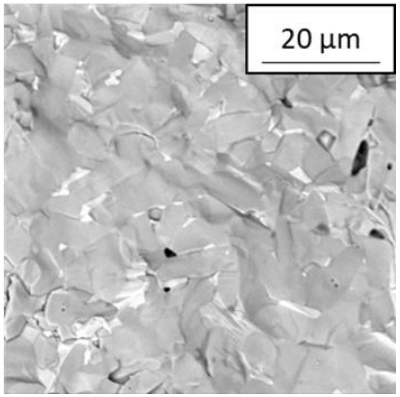




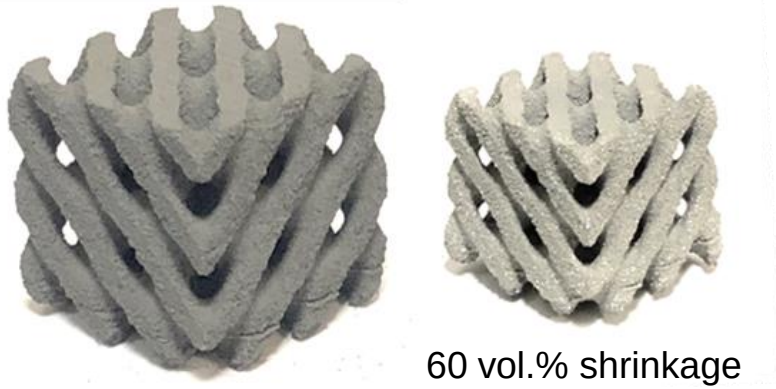
Using conventional powders and sizes required custom mods, 31-39% green density

Sintering Development

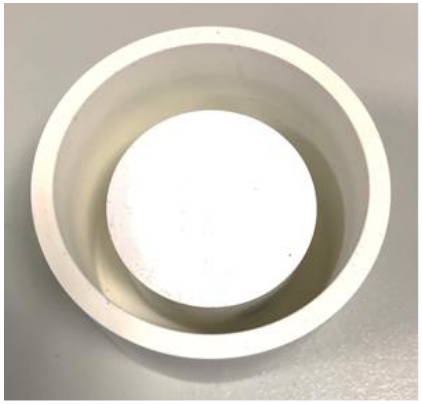
Coupon development (up to 98% dense)

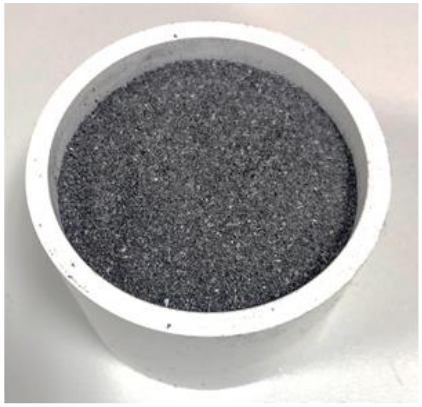


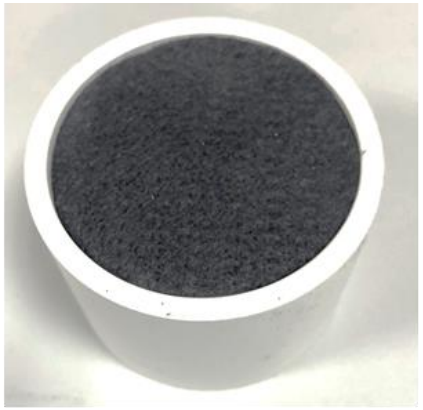
Subscale component (up to 96% dense)



60 vol.% shrinkage

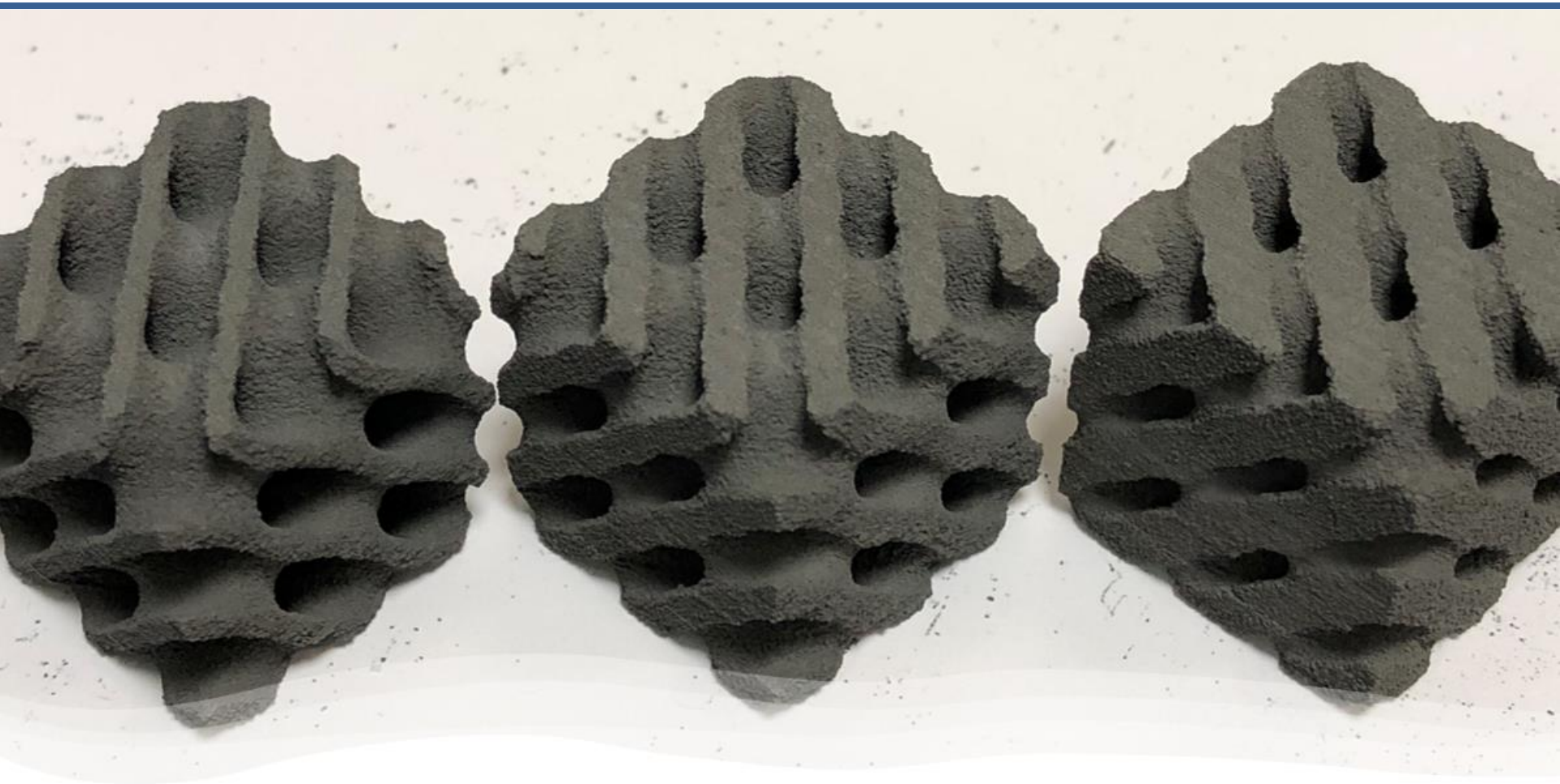






Obtaining closed porosity and uniform shrinkage demonstrates basic manufacturing feasibility

Thank you! Questions?

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