Novel Surface Finishing Approach for Additively Manufactured RF Components for Fusion Reactor Applications

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Laser Powder Bed Fusion (L-PBF)

- Advanced manufacturing technique
- Freeform fabrication/complex shape capability
- Suitable for difficult to machine/fabricate materials
- *Produces high levels of granular roughness/surface waviness*
- *Commonly produces near surface porosity*

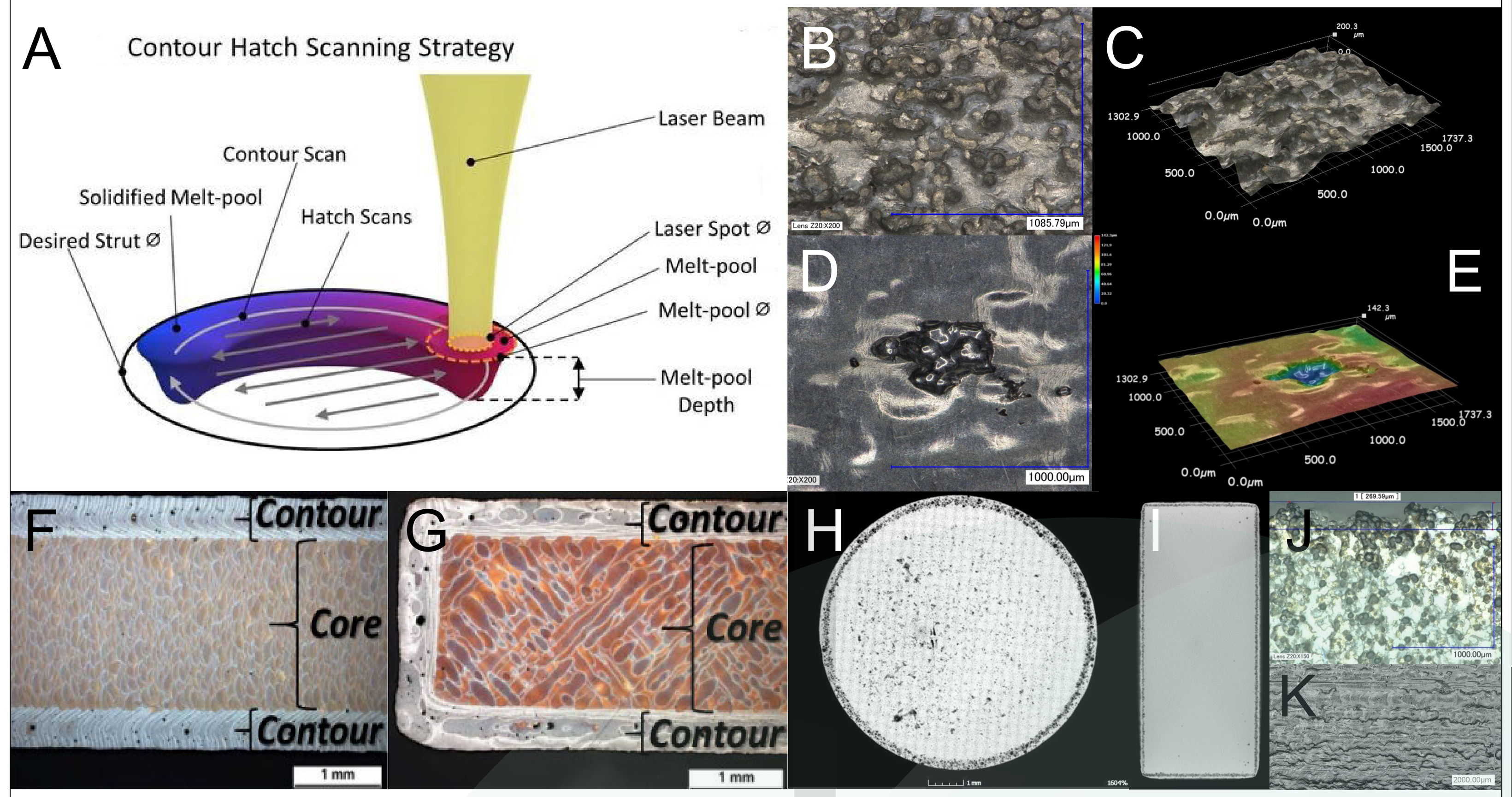

Figure 1: (A) Schematic representation of traditional contour scanning strategies[6]; (B) & (C) Micrographs of a EBM Ti-6Al-4V surface showing significant melt-pool derived roughness/waviness; (D) & (E) Micrographs of a L-PBF Ti-6Al-4V samples showing contour-hatch interface porosity at ~160 µm depth; (F) & (G) Micrographs of etched cross-sections of L-PBF AlSi10Mg samples showing the microstructure of an orthogonal cut (F), and a parallel cut (G) along the build direction[7]; (H) & (I) Micro X-ray CT Scan composites showing subsurface porosity of L-PBF A6061-R2 (H), and IN-625 (I); (J) Micrograph of L-PBF Ti-6Al-4V showing significant granular roughness and surface waviness; and (K) Micrograph of L-PBF 17-4 PH showing defined laser-based layer lines

GRCop-84 & GRCop42

- Novel dispersion strengthening copper alloys (Cr_2Nb) [1]
- Stable up to at least 800° C[1]
- Maintains tensile strength up to/above 700 ° C[1]
- Low thermal expansion → lower creep stress & smaller LCF strain ranges → increased life vs. other Cu alloys[1]
- Demonstrated printability via L-PBF[1,3]
- *Exhibit equal or greater as-printed roughness & near surface porosity versus more common L-PBF alloys*
- *Powder removal/blockage from complex geometries can be an issue*

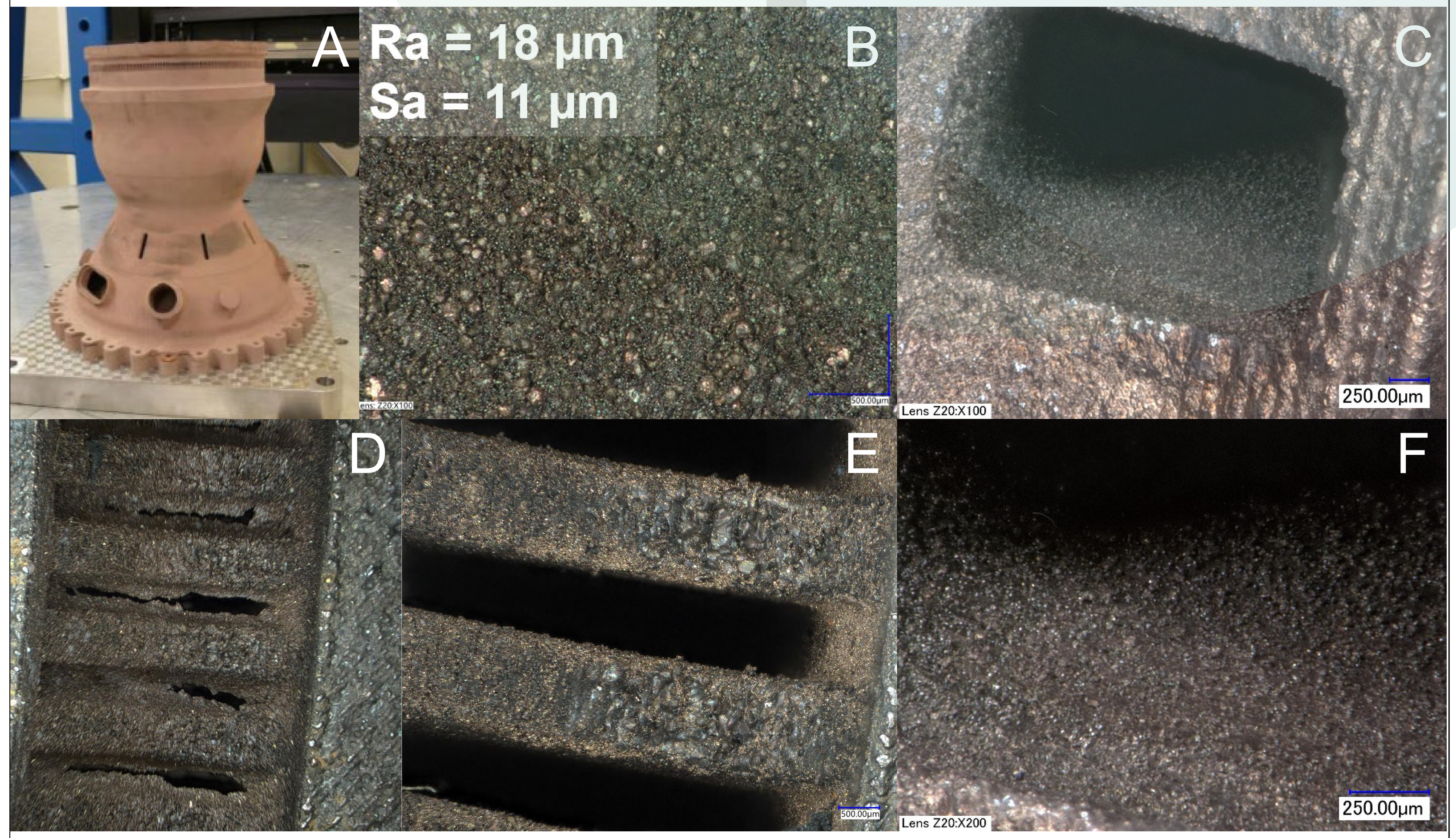

Figure 2: (A) L-PBF GRCop-42 Combustion Chamber[3]; (B) Micrograph and roughness measurements of as-printed L-PBF GRCop-42; (C) & (F) Micrographs of as-printed L-PBF GRCop-84 channels at 100x (C), and 200x (F); (D) & (E) Micrographs of as-printed GRCop-42 channels showing partial closure due to excess powder fusion (D), and high as-printed granular roughness (E)

Novel Surface Finishing Requirement

- Traditional Methods are Inadequate
  - Chemical Milling = lacks requisite roughness reduction
  - Abrasive Mass Finishing = not viable on interior/internal surfaces
  - Machining = line-of-sight limitations
  - Electropolishing = highly non-uniform material removal through internal surfaces
- Novel Approach
  - Individual and/or combinatory application of Chemical Polishing (CP) and Chemical-Mechanical Polishing (CMP)
  - CP = chemical dissolution with enhanced planarization capabilities
    - Geometrically agnostic & capable of substantial roughness reduction; some waviness may remain
  - CMP = applicable to complex internal geometries & capable of generating near-mirror surface roughness
    - Utilizes self-limiting, self-assembling monolayer (SAM) reaction to lower the required force to affect material removal
    - Exceptional planarization capability; can eliminate waviness

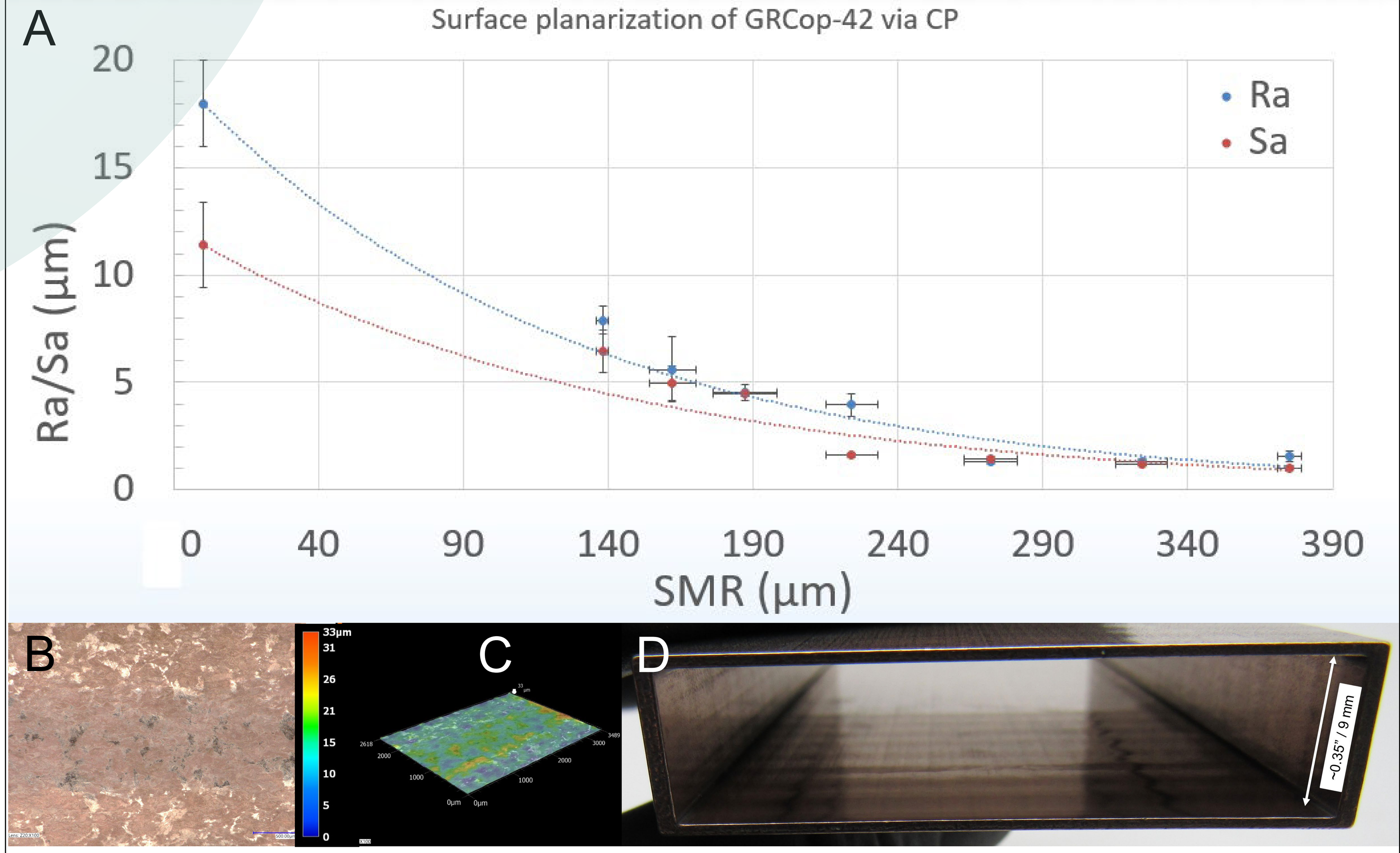

Figure 3: (A) Roughness reduction versus surface material removal graph for L-PBF GRCop-42 processed via CP; (B) & (C) Micrographs of L-PBF GRCop-42 after CP showing elimination of granular roughness and substantial planarization; (D) L-PBF GRCop-84 Waveguide after CP+ CMP (courtesy of MIT PSFC)

High Field Side Lower Hybrid Coupler

- Potential for higher current drive efficiency & better current profile control[2]
- Cu alloys are ideal for RF launchers vs. steel or Ni-Cr superalloys[4]
- L-PBF is advantageous for fabrication of enclosed structure and large material removal/thin-wall component requirements for these applications[4]
- *Low roughness surfaces (~0.3 µm Ra) are required to achieve desired RF performance[4,5]*

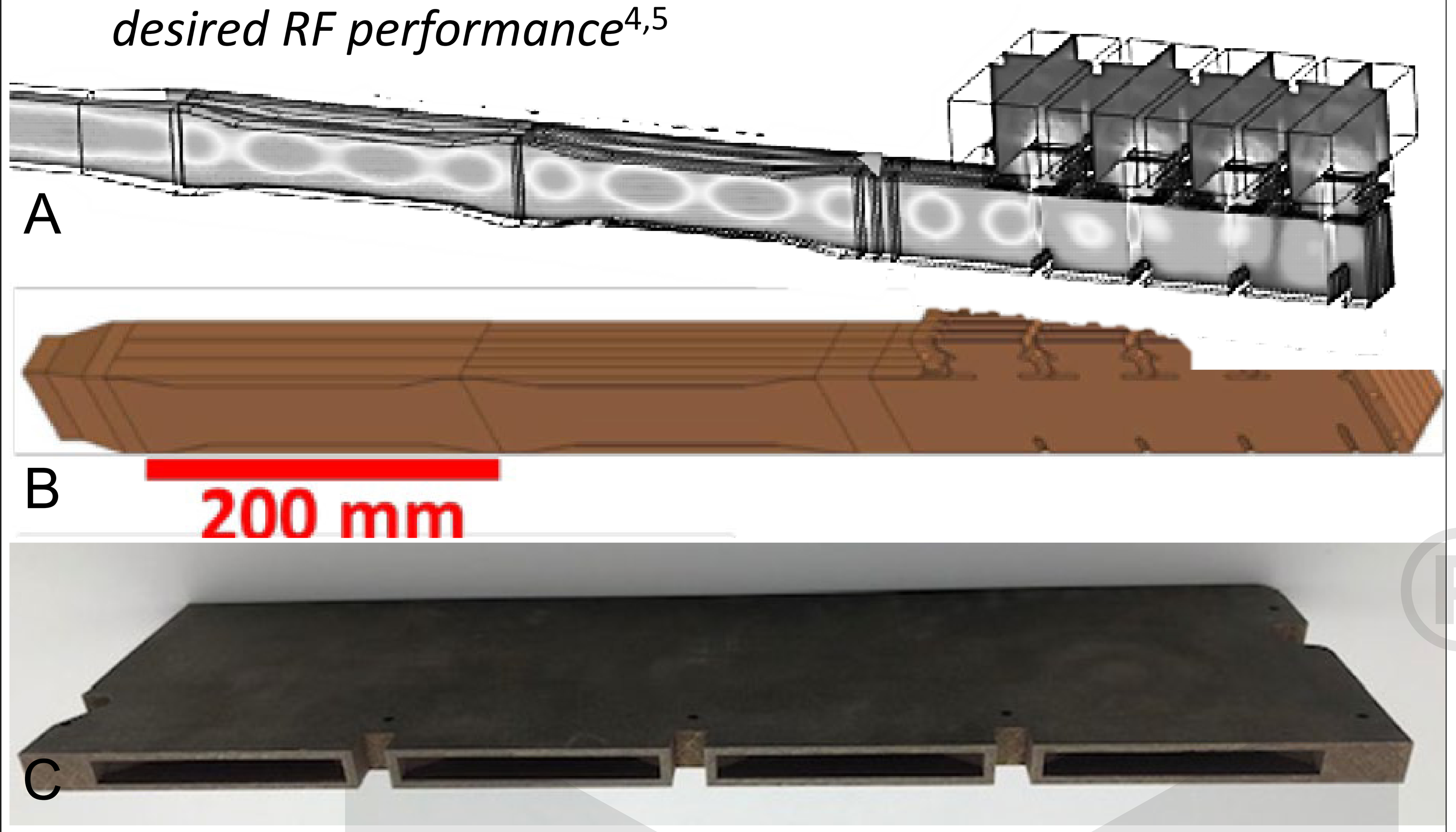

Figure 4: (A) & (B) Schematic representation Lower Hybrid Current Drive (LHCD) Launcher[4,5]; (C) L-PBF GRCop-84 Poloidal Splitter (courtesy of MIT PSFC)

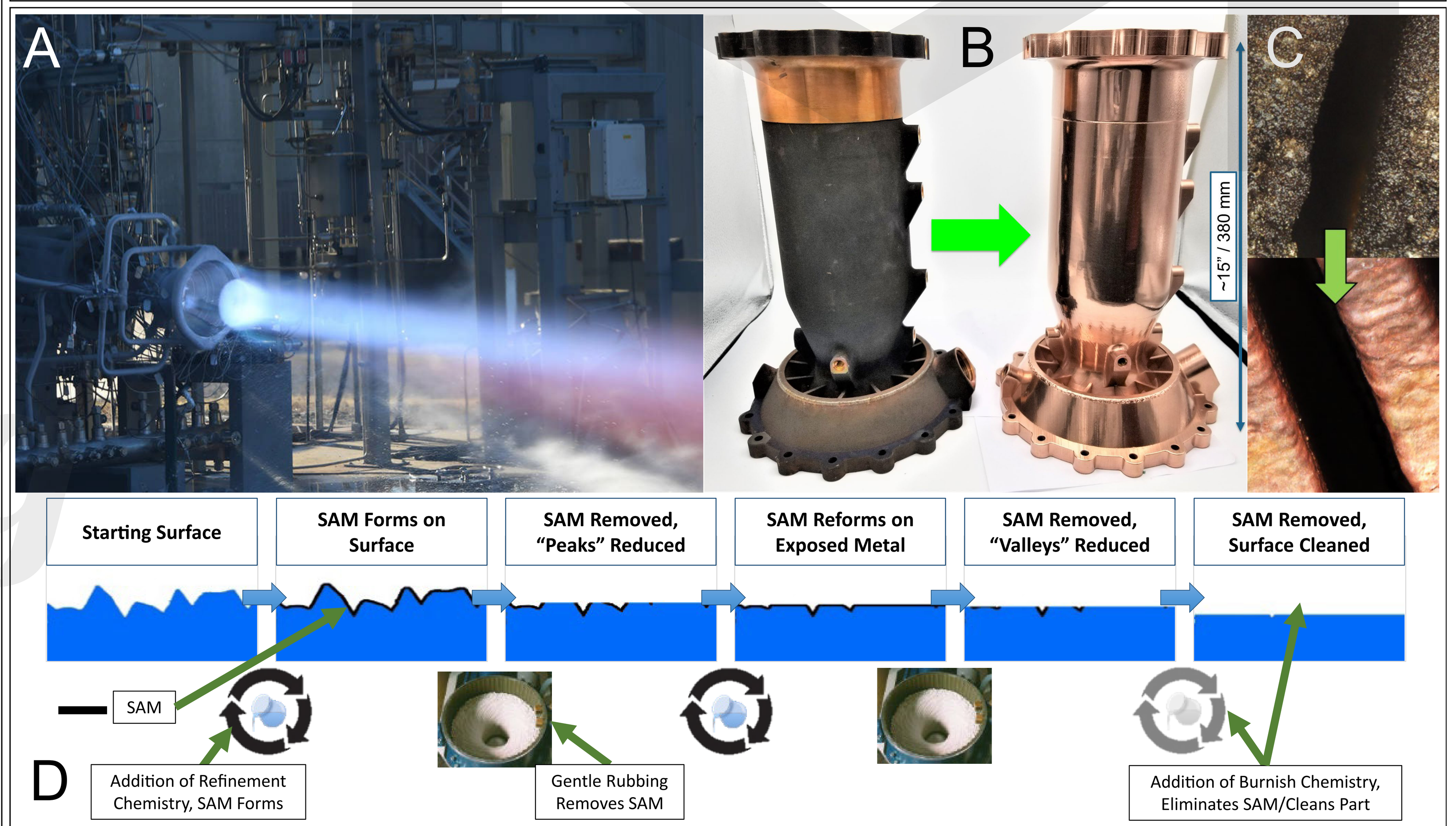

Figure 5: (A) Hot fire testing of 7K LLAMA rocket engine with L-PBF GRCop-42 combustion chamber with REM's CP+CMP surface finishing[8]; (B) 7K LLAMA combustion chamber (courtesy of NASA MSFC); (C) L-PBF GRCop-42 as-printed (top) and after CP cooling channels; (D) Process outline of the CMP process

References

[1] Ellis, D.L., "GRCop-84: A High-Temperature Copper Alloy for High-Heat-Flux Applications", NASA/TM2005-213566

[2] Bonoli, P.T., Wukitch, S.J., "PMI Challenges and Path towards RF Sustainment of Steady State Fusion Reactor Plasmas", https://burningplasma.org/activities/uploads_tec/FESAC_TEC_Wukitch_HFS-LHCD.pdf

[3] P.R. Gradl, C. S. Protz, D. L. Ellis, S. E. Greene, "Progress in Additively Manufactured Copper-Alloy GRCOP-84, GRCOP-42, and Bimetallic Combustion Chambers for Liquid Rocket Engines". 70th International Astronautical Congress (IAC), Washington D.C., United States, 21-25 October 2019.

[4] A.H. Seltzman, S.J. Wukitch, "RF losses in selective laser melted GRCop-84 copper waveguide for an additively manufactured lower hybrid current drive launcher", Fusion Engineering and Design, Volume 159, 2020, 111762, ISSN 0920-3796, https://doi.org/10.1016/j.fusengdes.2020.111762. https://www.sciencedirect.com/science/article/pii/S0920379620303100)

[5] A.H. Seltzman, S.J. Wukitch, "Surface roughness and finishing techniques in selective laser melted GRCop-84 copper for an additive manufactured lower hybrid current drive launcher", Fusion Engineering and Design, Volume 160, 2020, 111801, ISSN 0920-3796, https://doi.org/10.1016/j.fusengdes.2020.111801. (https://www.sciencedirect.com/science/article/pii/S0920379620303495)

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[7] R. Wagener, B. Möller, T. Melz, and M. Scurria, in SAE Tech. Pap. (SAE International, 2019).

[8] https://www.nasa.gov/centers/marshall/news/releases/2020/3d-printed-rocket-engine-parts-survive-23-hot-fire-tests.html