National Aeronautics and Space Administration

Effect of Tungsten L-PBF Feedstock Modification on Performance in Bending

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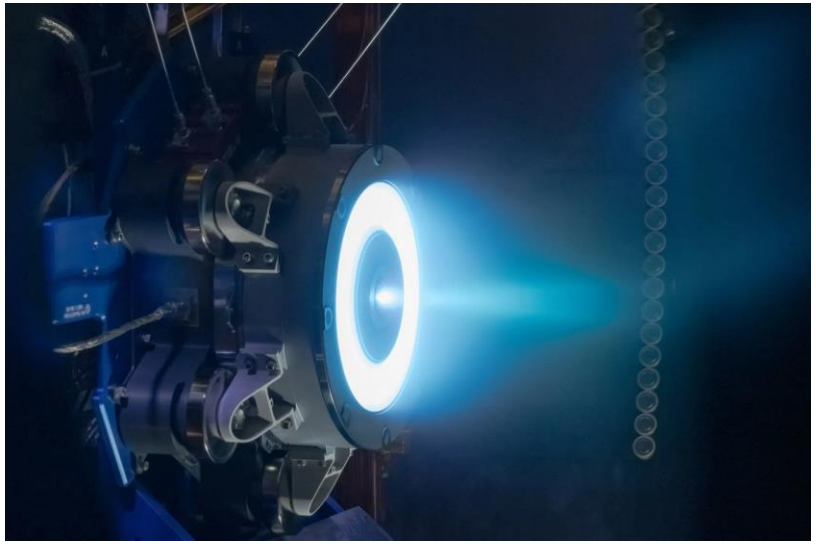
Introduction

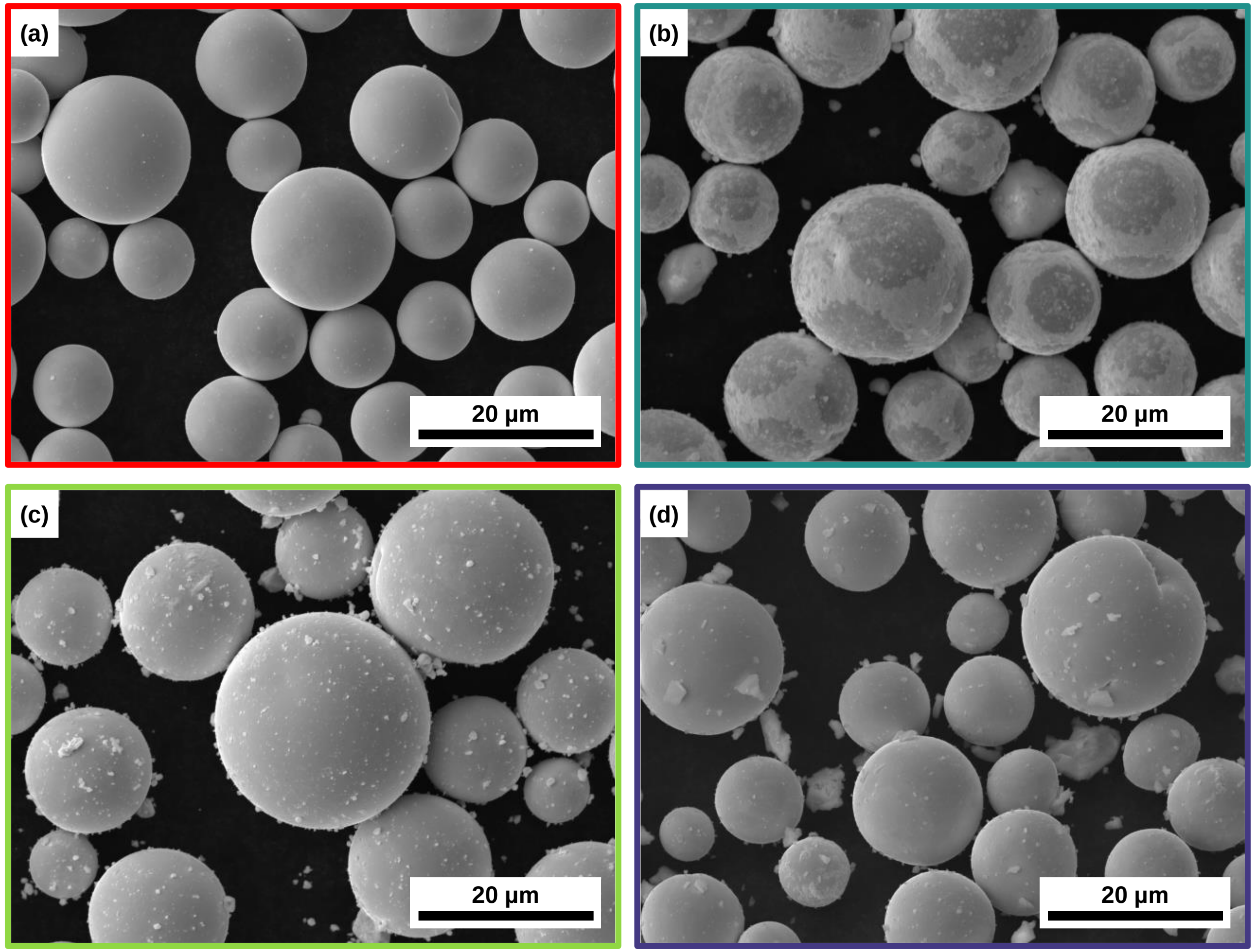
- Additively manufactured tungsten is a candidate material for high-temperature aerospace and nuclear fusion/fission applications.
- The printability of pure tungsten is challenged by cracking defects from the metal's high BDTT and low solubility of interstitial impurities. Micro-alloying and dispersoid additions can alter tungsten printability and strength.
- In this work, pure tungsten L-PBF feedstock was modified with 1 wt% additions of ceramic compound nano-powders. Flexural strength and microstructural characterization assessed the effect of the feedstock modification on mechanical performance.



The Advanced Electric Propulsion System (AEPS) inside a vacuum chamber at NASA Glenn Research Center. Credit: NASA / Jef Janis

Materials and Powder Processing

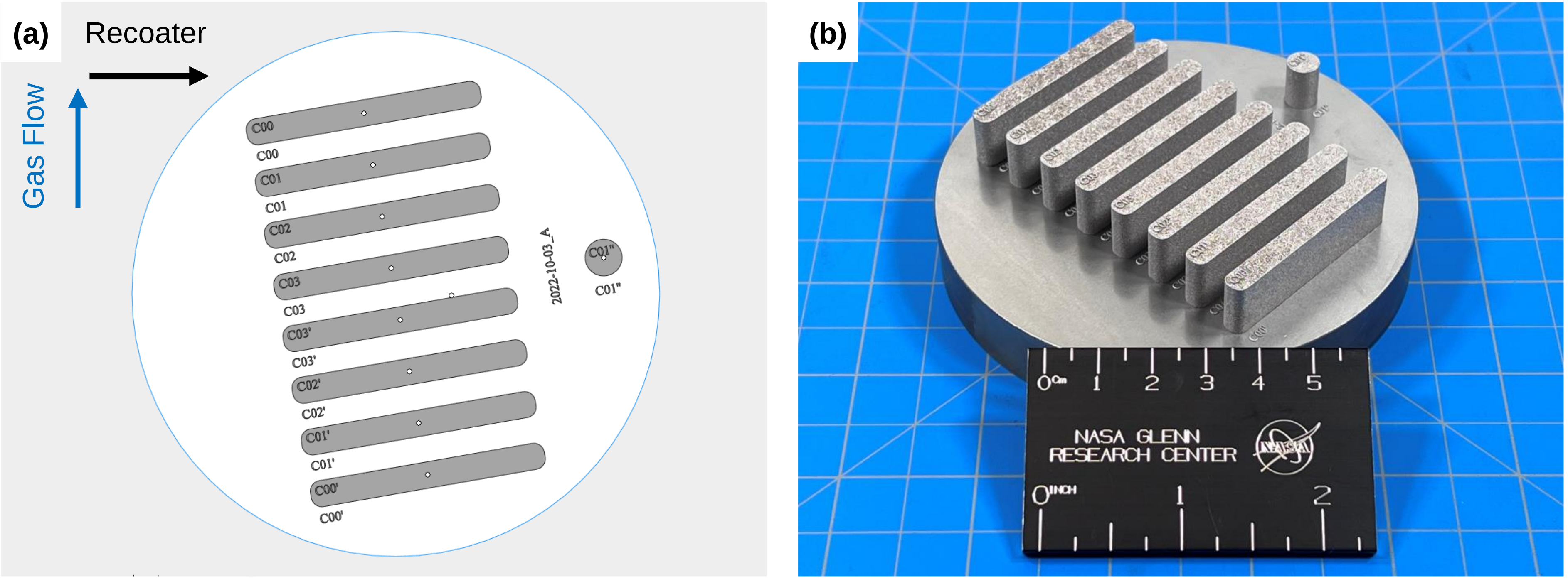
- Barstock
  - Wrought (worked)
  - Cast (electron beam)
- L-PBF Feedstock
  - **99.9% Tungsten**
    - D_{10} = 10 μm
    - D_{90} = 25 μm
- Nanoparticles
  - **HfO_2** (100 - 200 nm)
  - **HfC** (100 - 200 nm)
  - **ZrH_2** (1 - 5 μm)



SEM secondary electron images of (a) Pure tungsten, (b) Tungsten + 1 wt% HfO_2, (c) Tungsten +1 wt% HfC, (d) Tungsten + 1 wt% ZrH_2

Additive Manufacturing

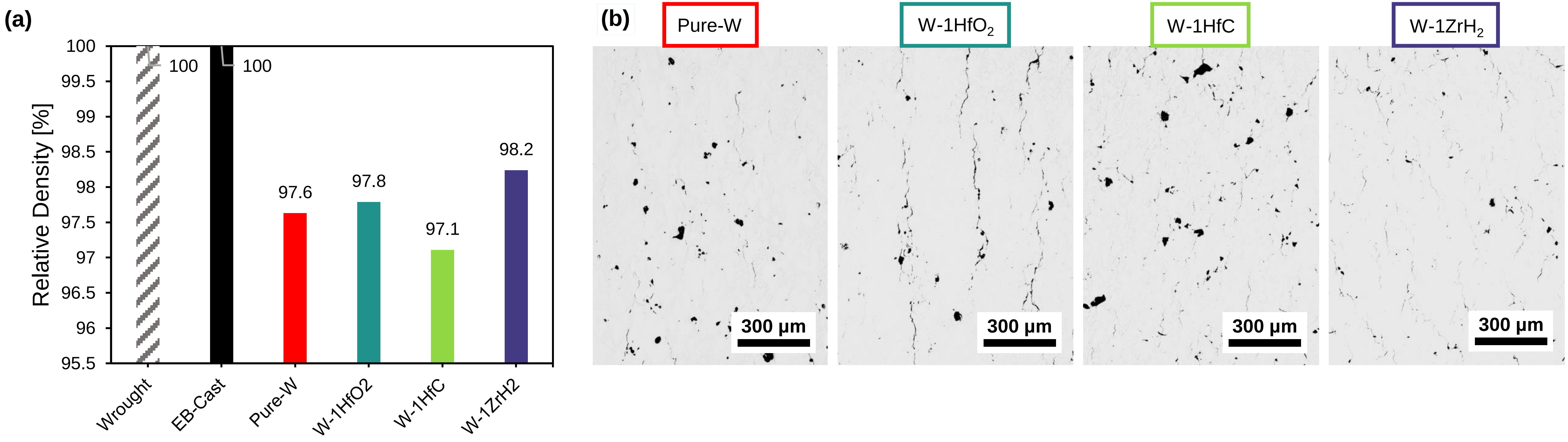
- *EOS M100*, 283 - 708 J/mm^3, < 200 ppm O_2



(a) Layout of specimens on the build plate and (b) The as-fabricated specimens

Printed Material Relative Density

- Determined via image analysis



(a) Relative density of all examined tungsten samples, (b) Example of optical micrographs from which image analysis determined L-PBF material relative density

Printed Material Chemical Composition

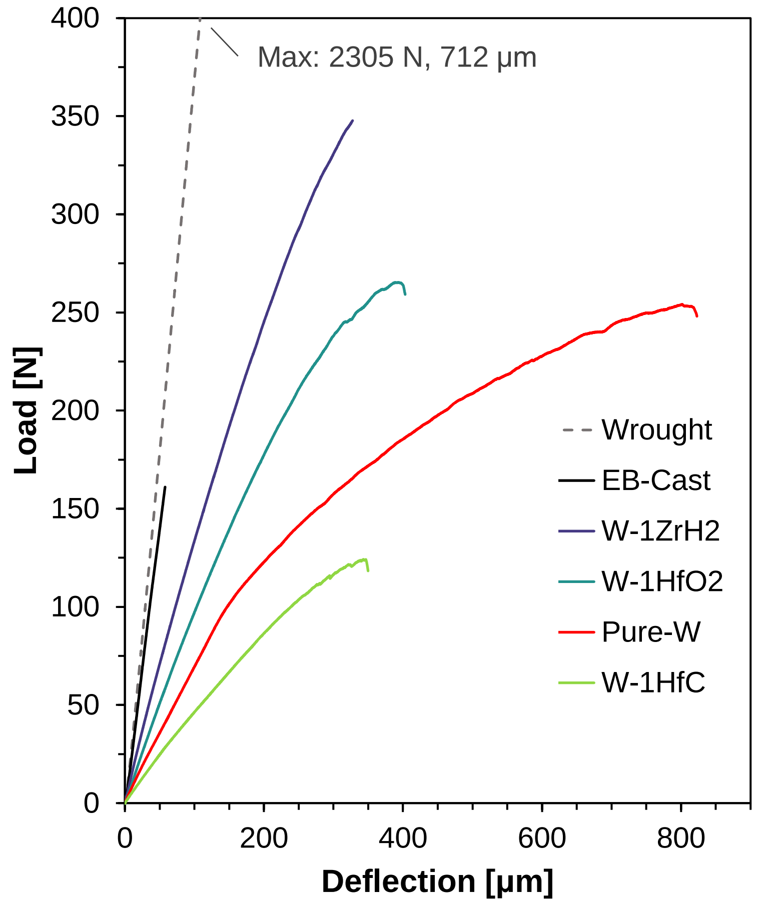
- Determined via ICP-MS and LECO Combustion analysis

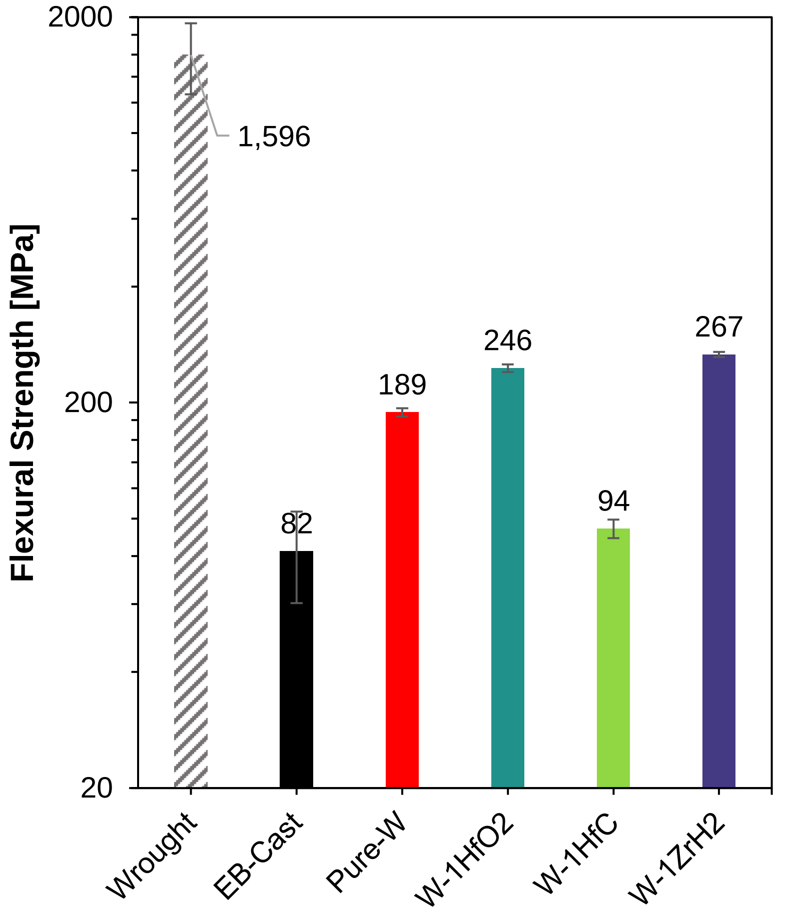
Material	W [wt%]	Hf [wt%]	Zr [wt%]	Ti [wt%]	O [ppm]	N [ppm]	C [ppm]	H [ppm]
Pure-W	99.9	-	-	-	36	-	-	-
W-1HfO_2	99.7	0.310	-	-	340	-	-	1
W-1HfC	99.1	0.840	0.010	-	14	11	350	1
W-1ZrH_2	99.4	0.015	0.570	0.002	88	17	-	1

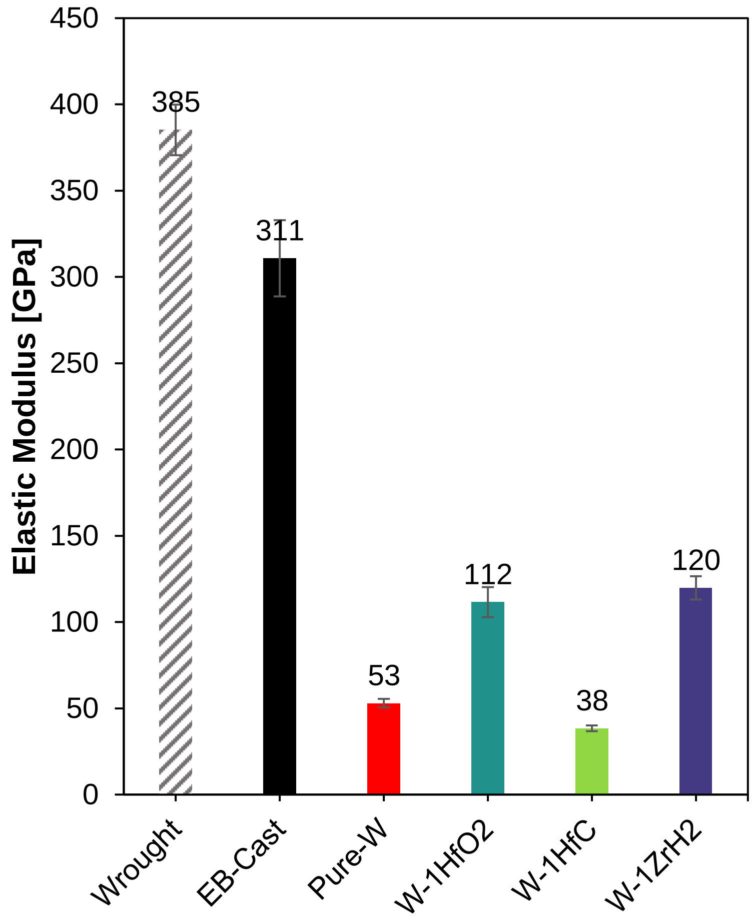
A dash symbolizes a result of "not detected"

Four-point Bend Testing

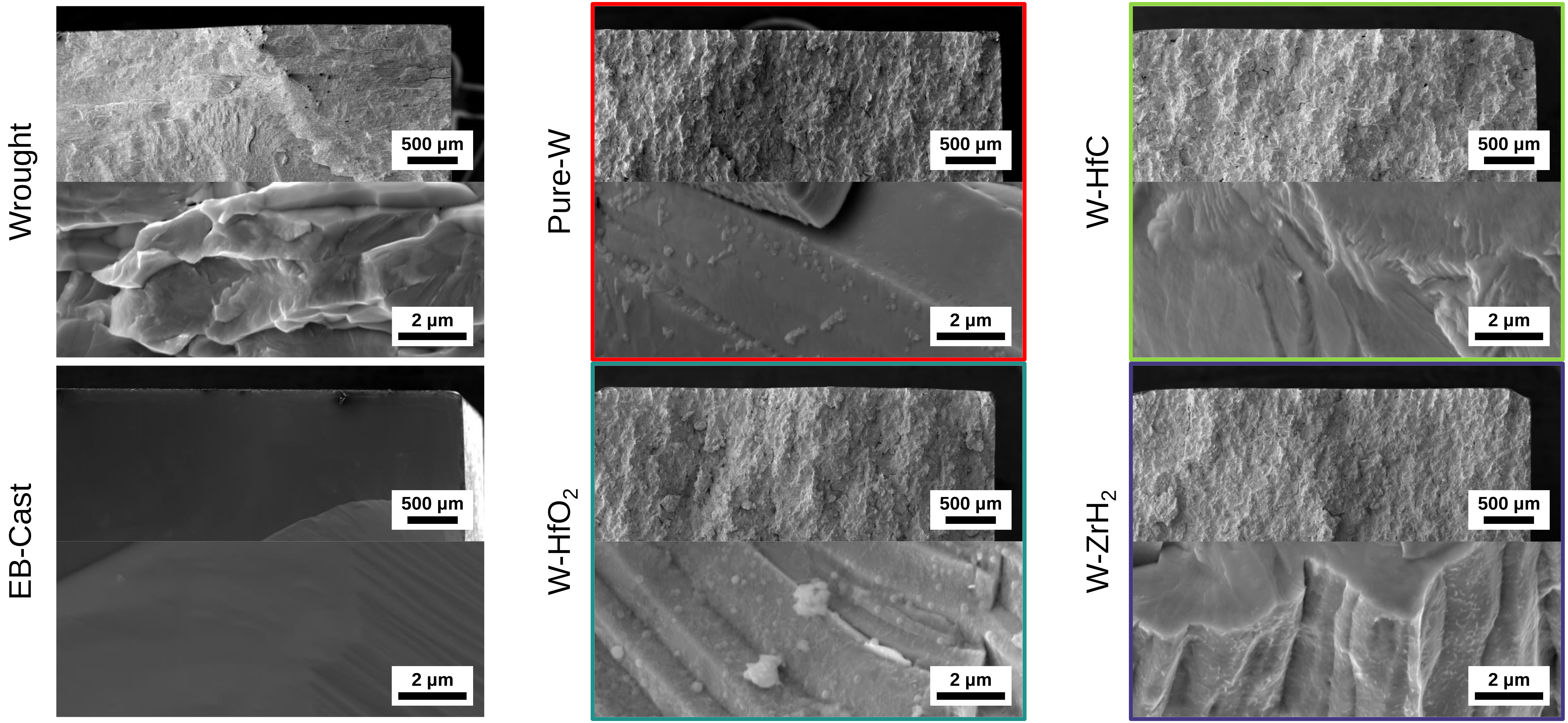
- Per ASTM C1161-18
  - Specimen Geometry: 45 x 4 x 3 mm







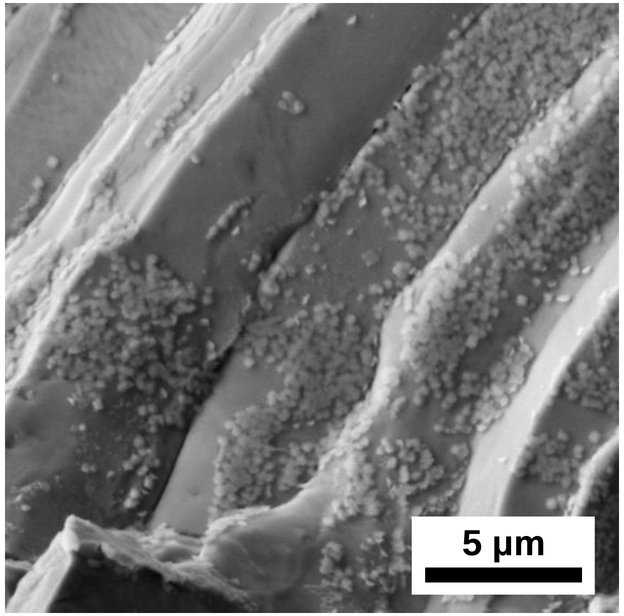
Fractography



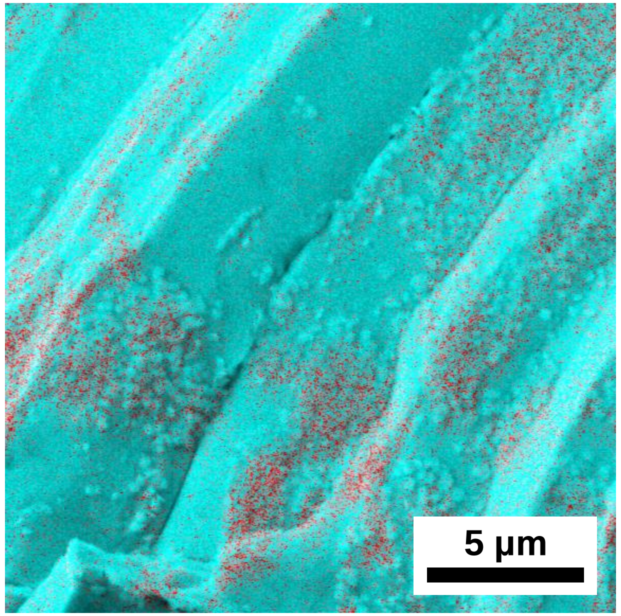
Fractography – EDS of Pure-W

(a)

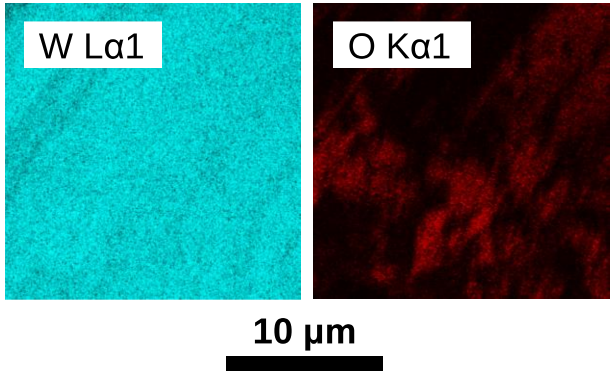
Electron Image



EDS Layered Image



Element Maps



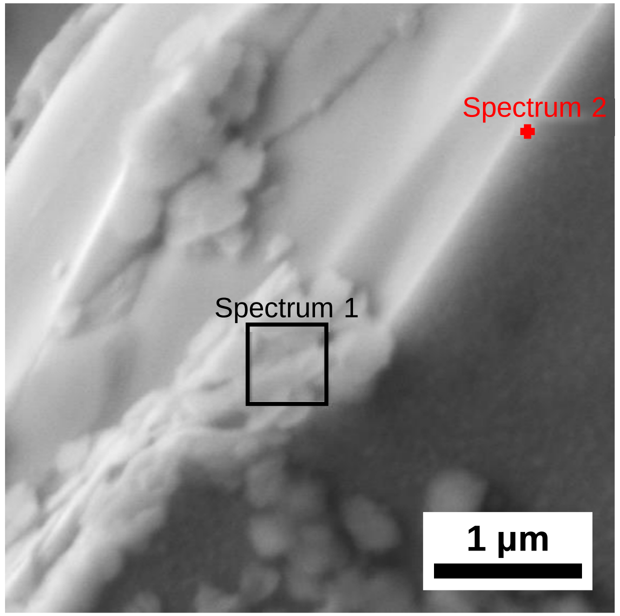
Spectrum Quant.

W 94.2 wt%

O 5.8 wt%

(b)

Electron Image



Spectrum 1

W 31.2 at%

O 68.8 at%

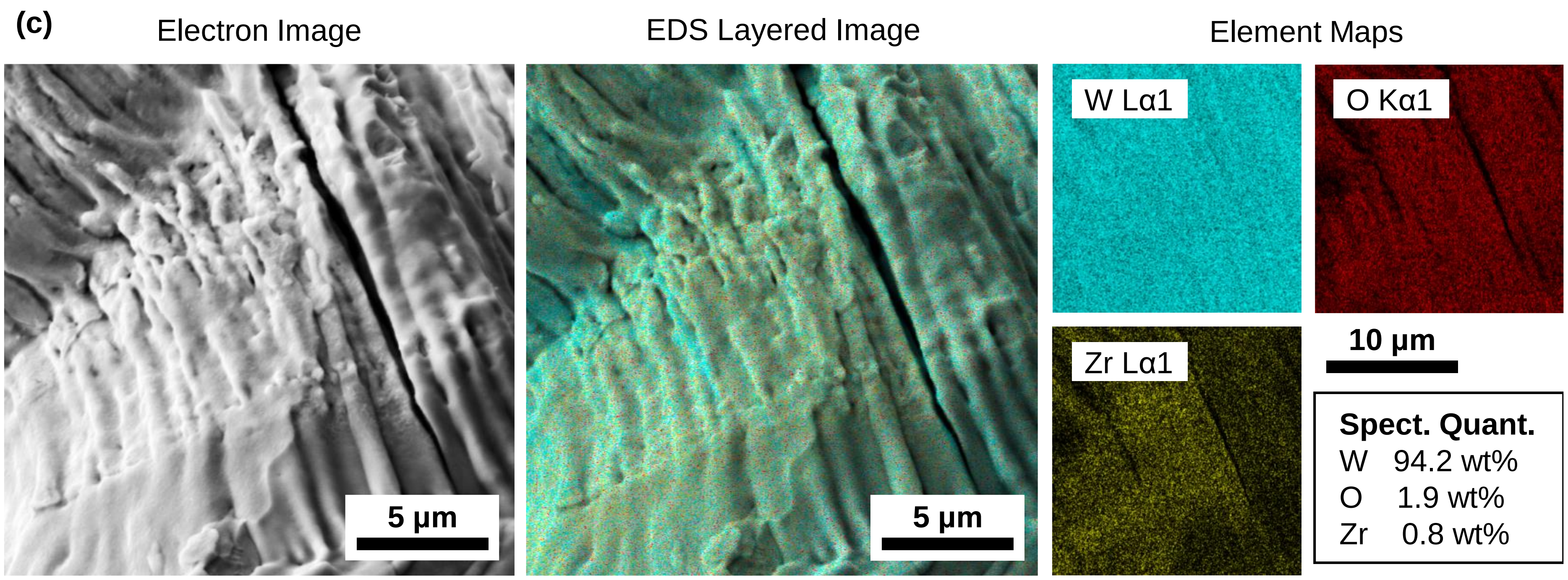
Spectrum 2

W 74.5 at%

O 25.5 at%

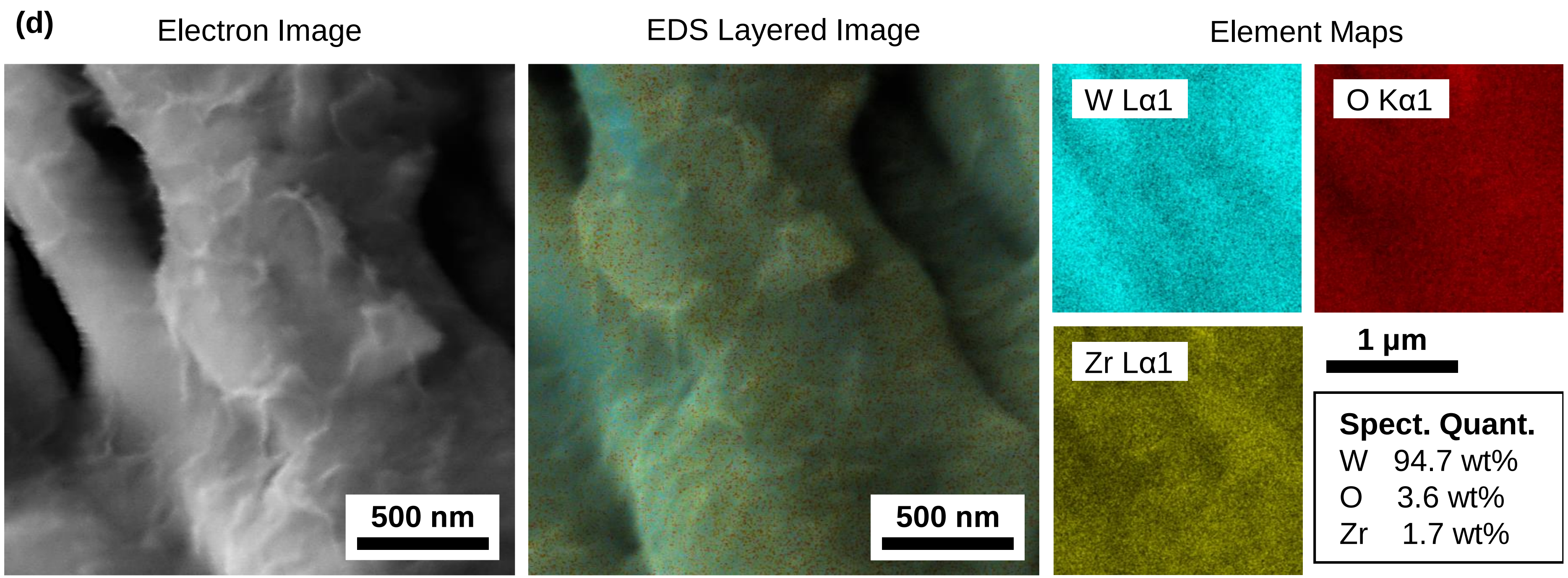
Secondary electron image, EDS layered map, elemental maps, and spectrum quantification of the (a) Pure-W fracture surfaces, alongside EDS verification of tungsten oxide particles on the Pure-W fracture surface (b).

Fractography – EDS of W-ZrH_2



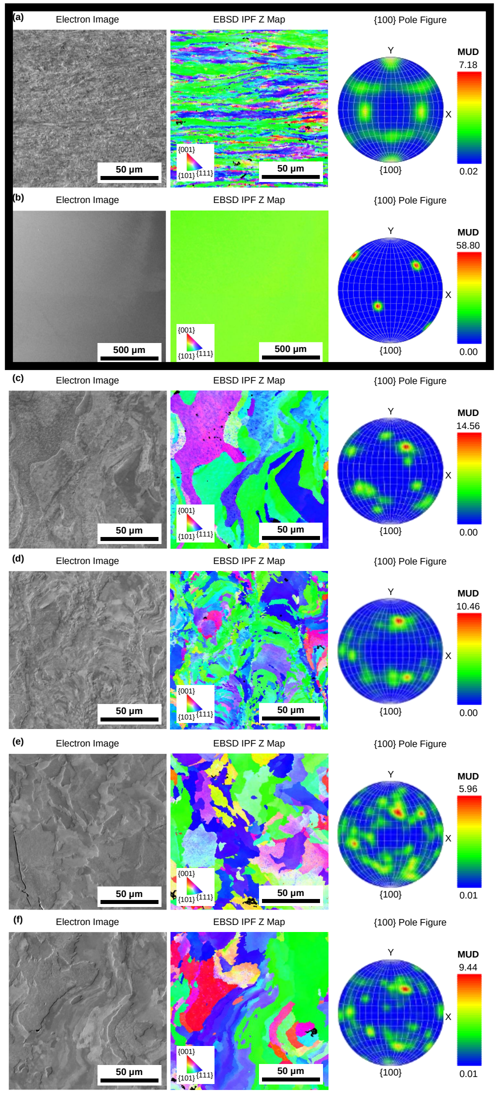
Secondary electron image, EDS layered map, elemental maps, and spectrum quantification of the (c,d) W-1ZrH_2 fracture surfaces

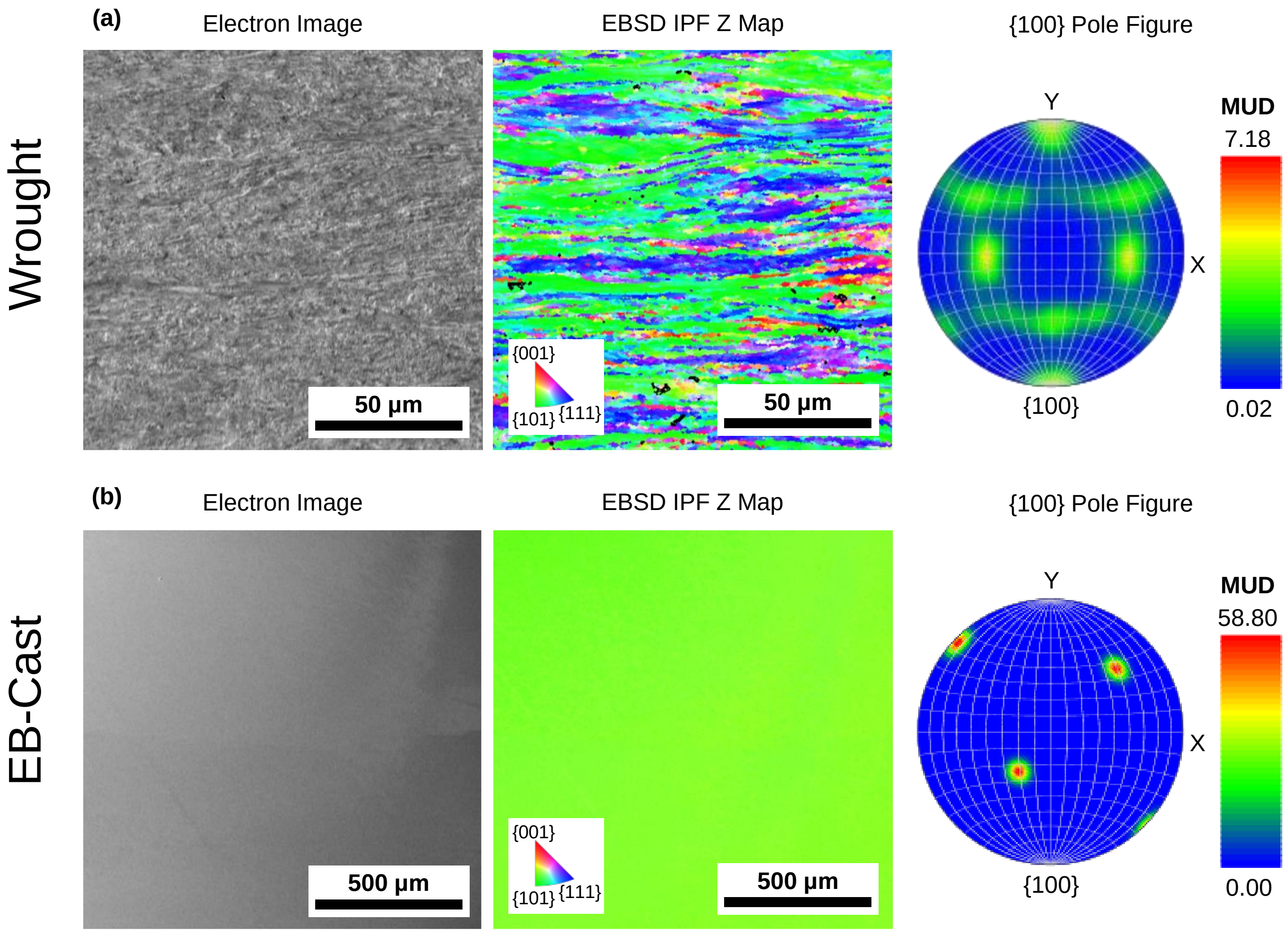
Fractography – EDS of W-ZrH_2 [High Mag]



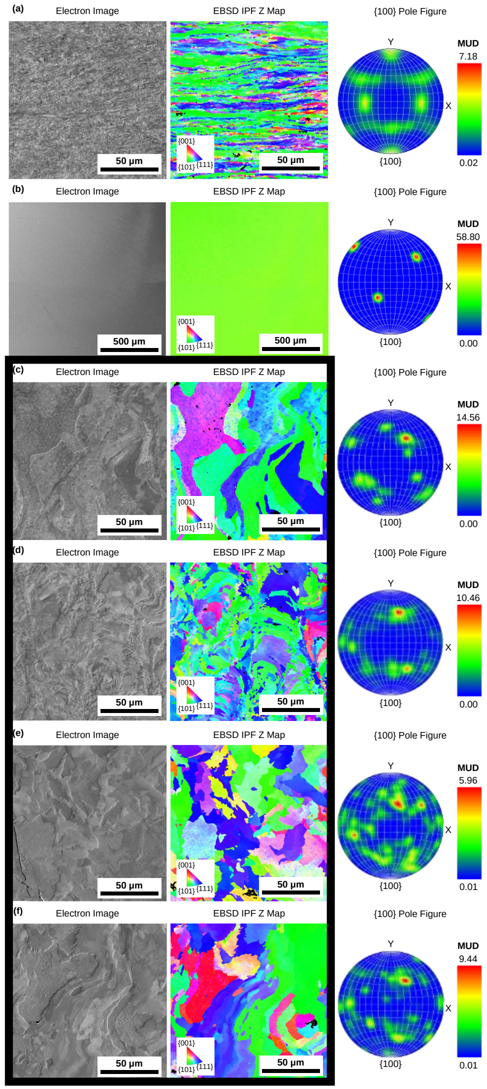
Secondary electron image, EDS layered map, elemental maps, and spectrum quantification of the (c,d) W-1ZrH_2 fracture surfaces

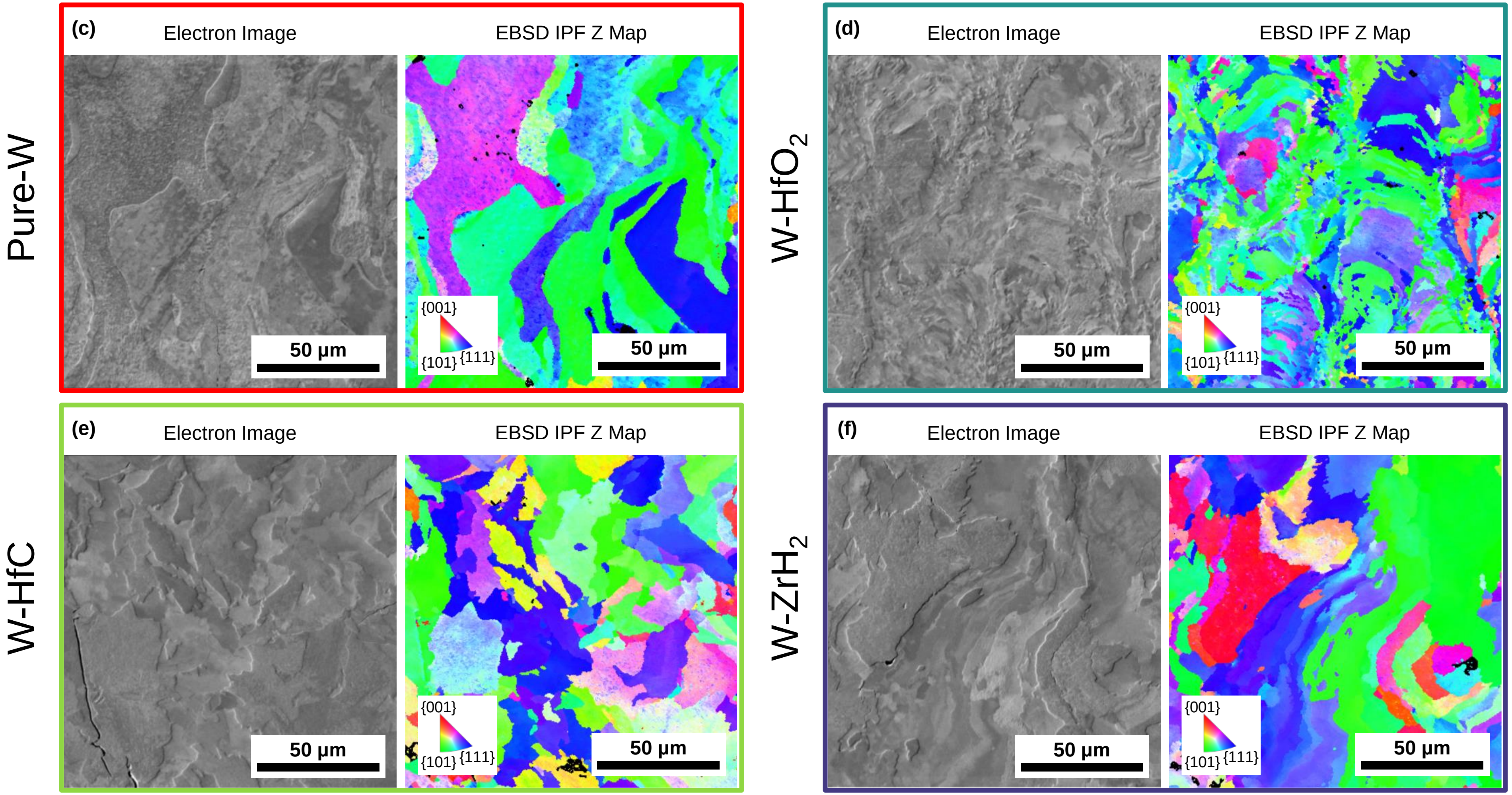
Microstructural Analysis – EBSD



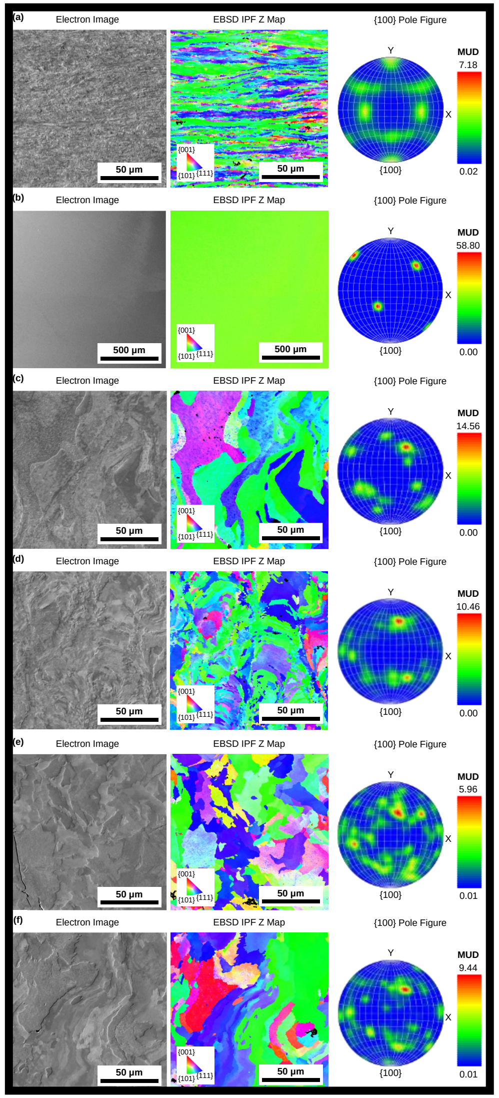


Microstructural Analysis – EBSD





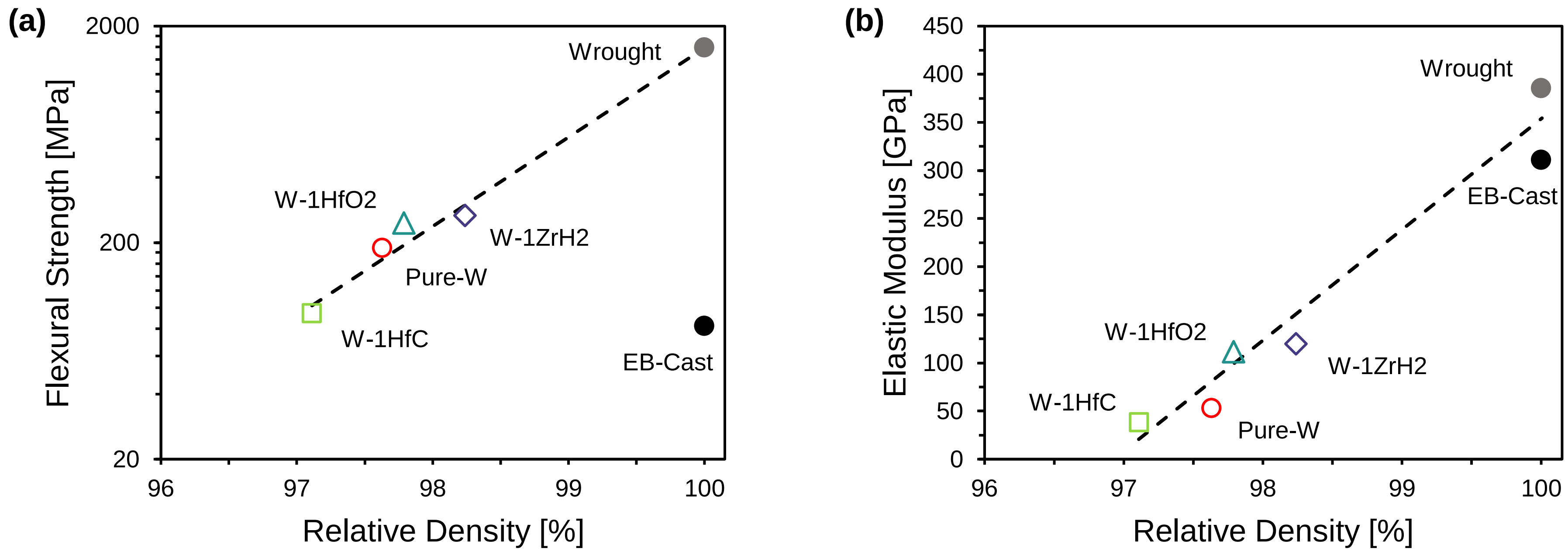
Microstructural Analysis – Grain Statistics vs. Strength



Material	Flex. Str. [MPa]	Elas. Mod. [GPa]	EBSD Grain Statistics (Average)				
			ECD [µm]	Len. [µm]	Asp. Rat.	GOS [°]	MOS [°]
Wrought	1595.9	385.3	3.37	8.88	3.36	4.21	9.55
EB-Cast	82.3	310.8	-	-	-	0.86	4.54
Pure-W	188.6	53.0	15.73	34.34	2.95	3.06	11.83
W-1HfO_2	245.6	111.5	4.27	7.50	1.99	1.96	5.01
W-1HfC	94.2	38.4	7.29	12.61	1.99	1.69	4.89
W-1ZrH_2	266.5	119.8	6.91	11.92	2.03	1.72	5.57

Discussion

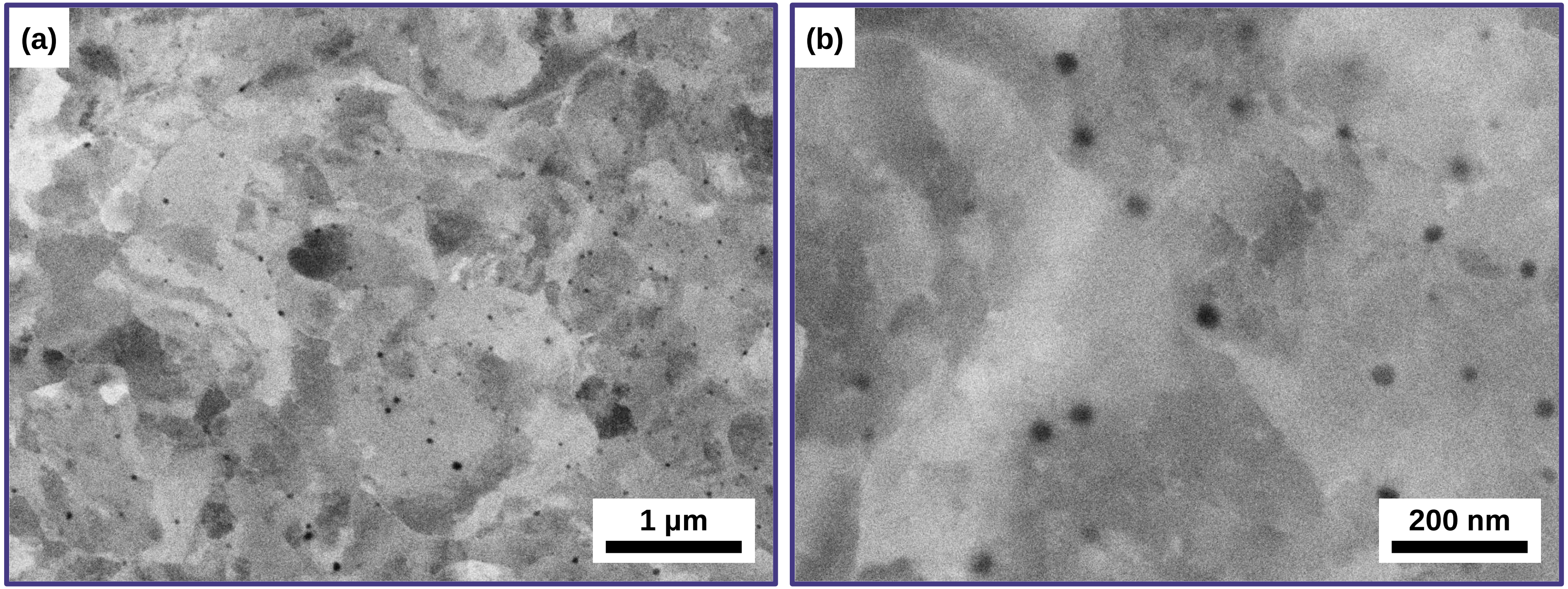
- Relative Density is consistent with Flexural Strength



Flexural strength (a) and Elastic modulus (b) vs. relative density for the Wrought, EB-Cast, and L-PBF consolidated materials

Discussion

- $2ZrH_2$ (s) + $3O_2$ (g) + Heat →$2ZrO_2$ (s) + $2H_2O$ (g)



Low (a) and High (b) magnification backscatter electron images of the W-1ZrH_2 material showing nano-sized particles throughout microstructure

Conclusions

1. Nano-scale **HfO_2** acheived the most uniform coating during powder processing
2. The **ZrH_2** addition increased L-PBF relative density compared to the **Pure-W** feedstock (97.6 % » 98.2 %)
3. The **ZrH_2** and **HfO_2** additions increased the L-PBF flexural strength and bending elastic modulus; however, overall performance is far from wrought worked material
4. Both **HfC** and **ZrH_2** additions reduce the detectable oxides on L-PBF fracture surfaces
5. All feedstock modifications reduced the grain ECD, but the **HfO_2** addition created finest L-PBF microstructure
6. Material relative density and micro-cracking had the largest influence on mechanical performance