A Comparison of Niobium Alloys C103 and Nb521

Eric Brizes [a]

Justin Milner [a]

[a] NASA Glenn Research Center, Cleveland, OH

TMS 2025. Las Vegas, NV. March 24

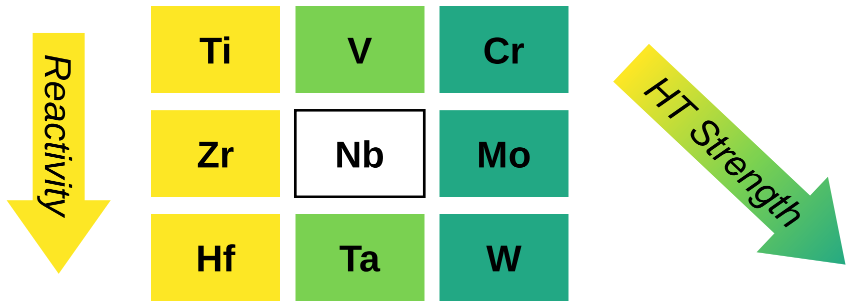
Introduction

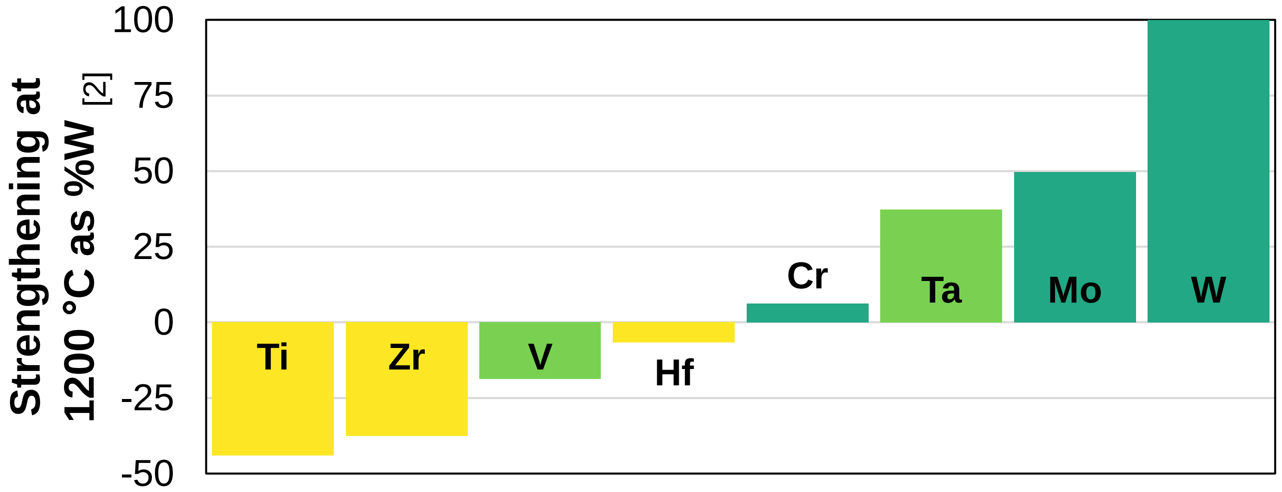
- Two niobium alloys have emerged as frontrunners for high-temperature applications in rocket propulsion systems: **C103** (Nb-10Hf-1Ti [wt%]), and **Nb521** (Nb-5W-2Mo-1Zr [wt%]).

- **C103** has historically provided satisfactory manufacturability/high-temperature performance, yet it is expensive due to the Hf content.
- **C103** is typically employed with a high-temperature oxidation-resistant coating (Si-20Cr-20Fe, tradename: R512E) that enables operation temperatures up to 1400 °C.

- **Nb521** leverages solid solution strengthening from W and Mo additions as well as precipitation strengthening via the formation of ZrC and Nb_2C.
- **Nb521** paired with $MoSi_2$ coatings, exhibits a claimed **3 to 5 times greater** high-temperature strength at 1600 °C compared to **C103**. [1]

Common Alloying Elements in Nb Alloys





Background

- **C103** was developed in the United States by *Boeing* & *Wah Chang Corp* in the 1960s. [3]
- **Nb521** alloy development began in the Soviet Union with the 5VMTs alloy (5ВМЦ in the Cyrillic alphabet) in the 1970s. [4]
- In the 1990s and throughout the 2000s, Chinese institutions conducted research and scaled production for niobium alloys based on the work of the Soviets.
- By 2007, a 5VMTs (called **Nb521** by the Chinese) liquid rocket engine was produced in China. The **Nb521** thrust chamber was successfully hot-fire tested at 1560 °C. [5]

Soviet Niobium Alloy Naming Convention

Element	Cyrillic	Latin	Soviet ID
Niobium	Ниобий	Niobiy	N
Tungsten	Вольфрам	Volfram	V
Tantalum	Тантал	Tantal	T
Molybdenum	Молибден	Molibden	M
Zirconium	Цирконий	Tsirkoniy	Ts
Carbon	Углерод	Uglerod	U
Nitrogen	Азот	Azot	A

e.g., 5ВМЦ :: 5VMTs :: Nb-5W-Mo-Zr

Background

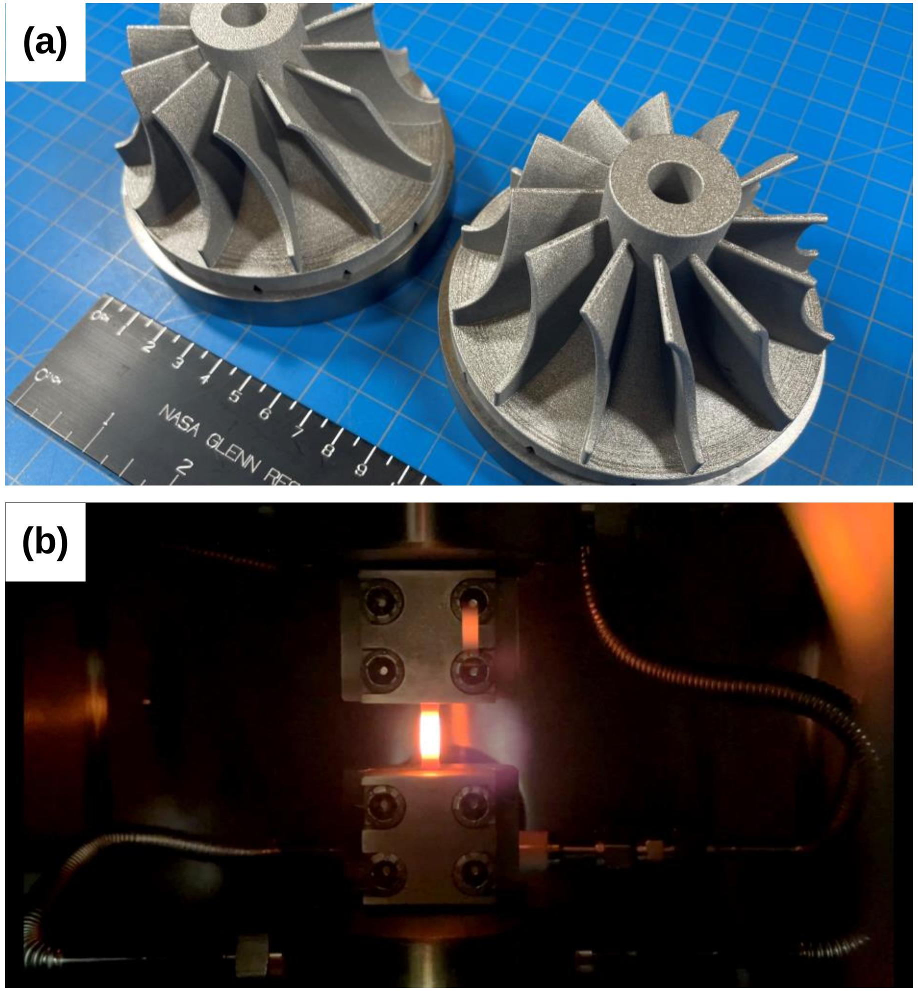
- **C103** was developed in the United States by *Boeing & Wah Chang Corp* in the 1960s. [3]
- **Nb521** alloy development began in the Soviet Union with the 5VMTs alloy (5ВМЦ in the Cyrillic alphabet) in the 1970s. [4]
- In the 1990s and throughout the 2000s, Chinese institutions conducted research and scaled production for niobium alloys based on the work of the Soviets.
- By 2007, a 5VMTs (called **Nb521** by the Chinese) liquid rocket engine was produced in China. The **Nb521** thrust chamber was successfully hot-fire tested at 1560 °C. [5]
- In 2015, the **Nb521** alloy was standardized in China with two grades, NbW5-1 and NbW5-2, corresponding to the two major producers. [6]
- To date, **Nb521** has found application in the reaction control system thrusters for China's Sinosat-6 and Nigeria's NigComSat-1R. [7]

Alloy	Nb521		C103
Spec. ID	**NbW5-1**	**NbW5-2**	**ASTM B391** [8]
Producer	Ningxia Orient Tantalum Industry Co. (OTIC)	NW Institute for Nonferrous Metal Research (NIN)	Various
Prod. Method	EB Smelted	Arc Smelted	-
Nb [wt%]	Bal.	Bal.	Bal.
W [wt%]	4.5 - 5.5	4.5 - 5.5	< 0.5
Mo [wt%]	1.7 - 2.3	1.5 - 2.5	-
Hf [wt%]	-	-	9.0 - 11.0
Zr [wt%]	0.7 - 1.2	1.4 - 2.2 ↑	< 0.7
Ti [wt%]	-	-	0.7 - 1.3
C [ppm]	500 - 1200	< 200 ⇩	< 150
O [ppm]	< 100	< 230 ↑	< 250
N [ppm]	< 100	< 150 ↑	< 100
Tensile Str. [MPa]	> 400	> 450 ↑	>370
Elongation [%]	> 20	> 25 ↑	> 20

"-" = not specified, room temperature mechanical properties

Motivation

- Additive manufacturing (AM) has dramatically expanded research interest in niobium-based alloys, and until recently **C103** was the only Nb-based alloy studied at scale for AM.
- Laser powder bed fusion (L-PBF) **Nb521** has been evaluated outside the US with reports detailing adequate printability and mechanical performance exceeding that of conventionally processed material. [9,10]
- Researchers at NASA Glenn Research Center and Marshall Space Flight Center have been evaluating **Nb521**, aiming to understand its performance and determine its ability to replace **C103**.
- In this work, **C103** and **Nb521** were produced via L-PBF, then microstructurally characterized and mechanically tested at elevated temperatures.



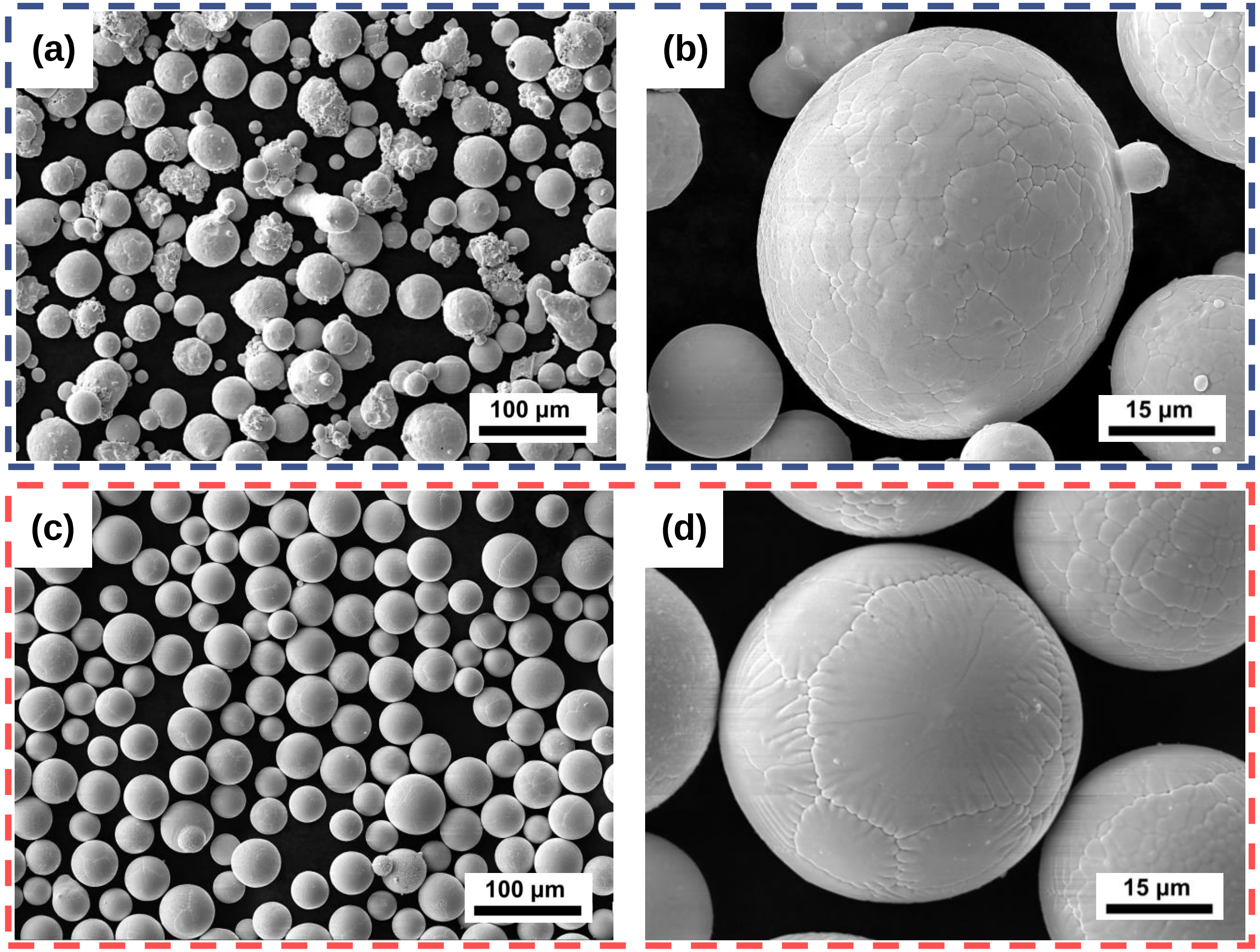
(a) L-PBF printed niobium alloy turbines and (b) elevated temperature mechanical test of a niobium alloy

Outline

1. **Materials and Processing**
   - L-PBF Consolidation
   - Chemical Analysis
   - As-built Microstructure
2. **Mechanical Testing**
   - Testing Equipment
   - Elevated Temperature Tension
   - Elevated Temperature Constant Load (Pseudo-Creep)
3. **Comparative Evaluation**
   - Microstructural Thermal Stability
   - Performance, Cost, and Other Properties
4. **Conclusions**

Materials

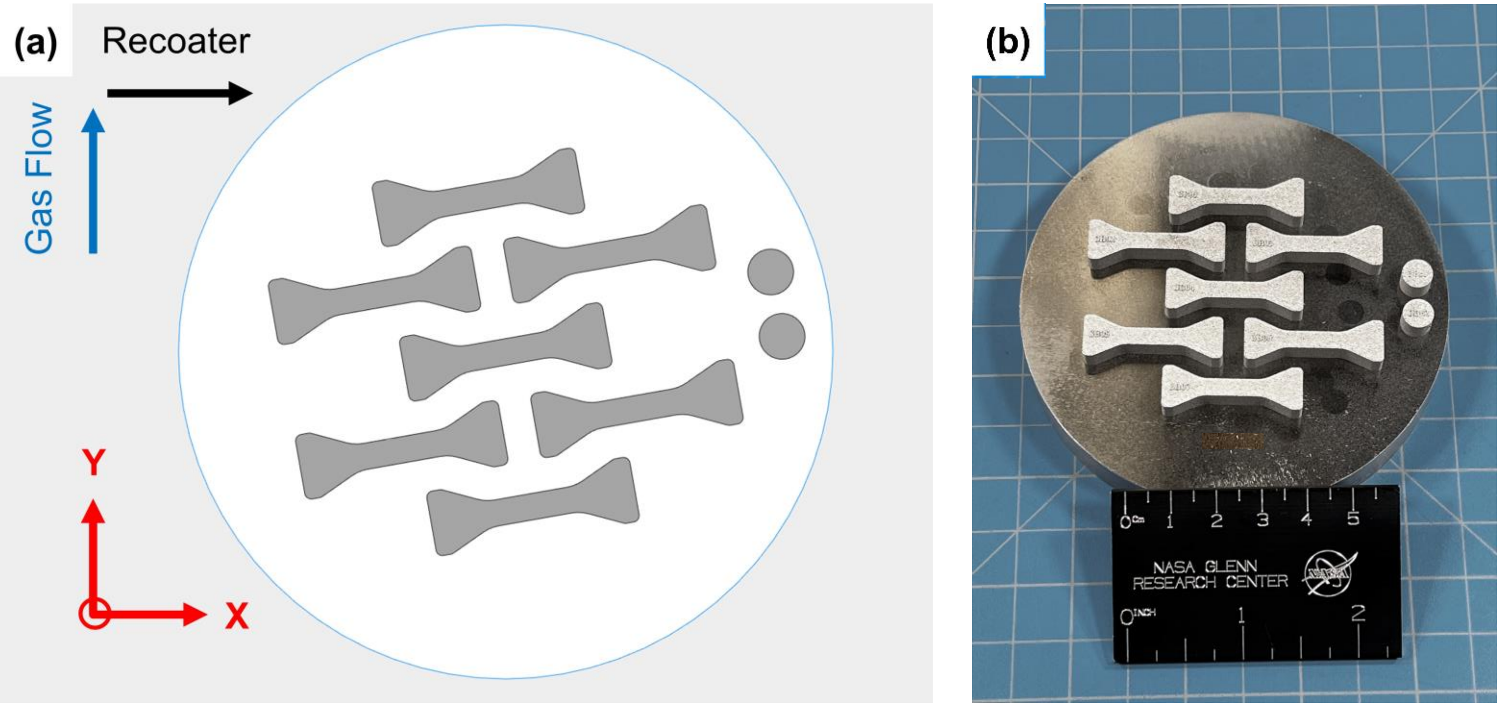
- L-PBF Powder Feedstock
  - **C103**
    - Produced via electrode induction melting inert gas atomization (EIGA)
    - Irregular morphology (presence of satellite/angular particles)
    - D_{10} = 16.3 μm
    - D_{90} = 51.5 μm
  - **Nb521**
    - Produced via plasma rotating electrode process (PREP)
    - Highly spherical, tighter PSD
    - D_{10} = 25.7 μm
    - D_{90} = 45.3 μm



Secondary electron SEM micrographs of the **C103** spherical powder at (a) low and (b) high magnification, and the **Nb521** spherical powder at (c) low and (d) high magnification

Laser Powder Bed Fusion

- *EOS M100*, Nb build plate, Argon atmosphere (< 10 ppm O_2), 31.5 x 10 x 1.5 mm bowties



(a) Schematic L-PBF build layout and (b) image of the completed **C103** build

L-PBF volumetric energy density (VED) and material density measurements

Material	**C103**	**Nb521**
VED [J/mm^3]	114.6	138.9
Archimedes Density [g/cc]	8.805	8.835
Optical Density [%]	99.92	99.96

Chemical Composition

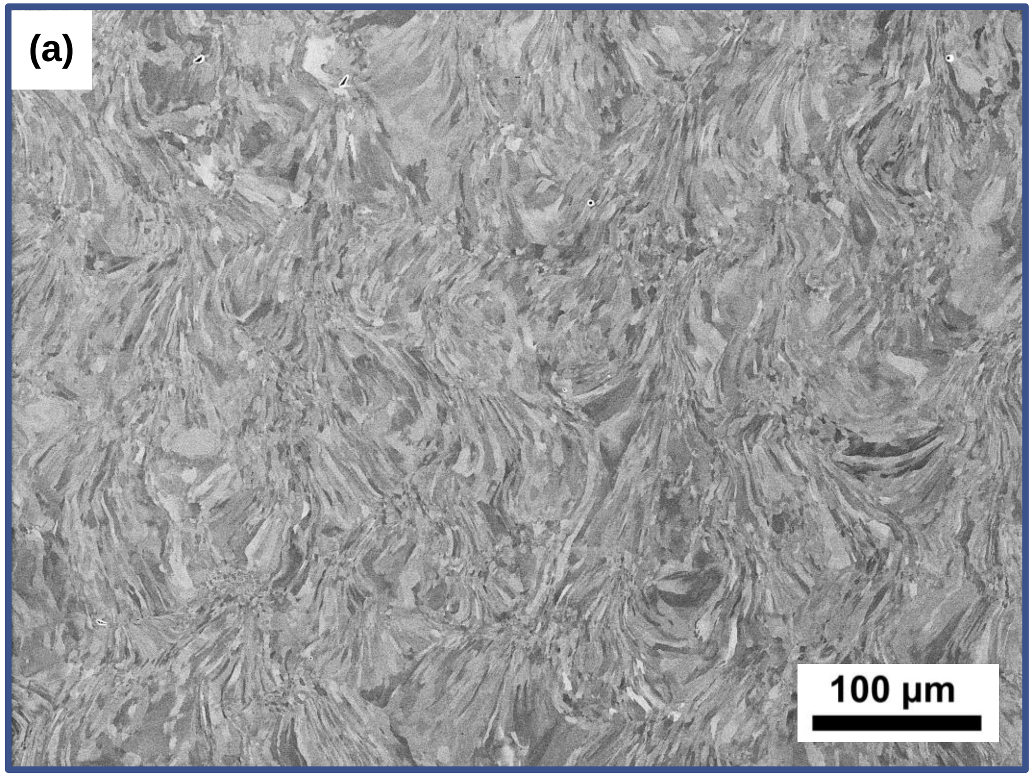
- Determined via SEM-EDS and LECO Combustion analysis

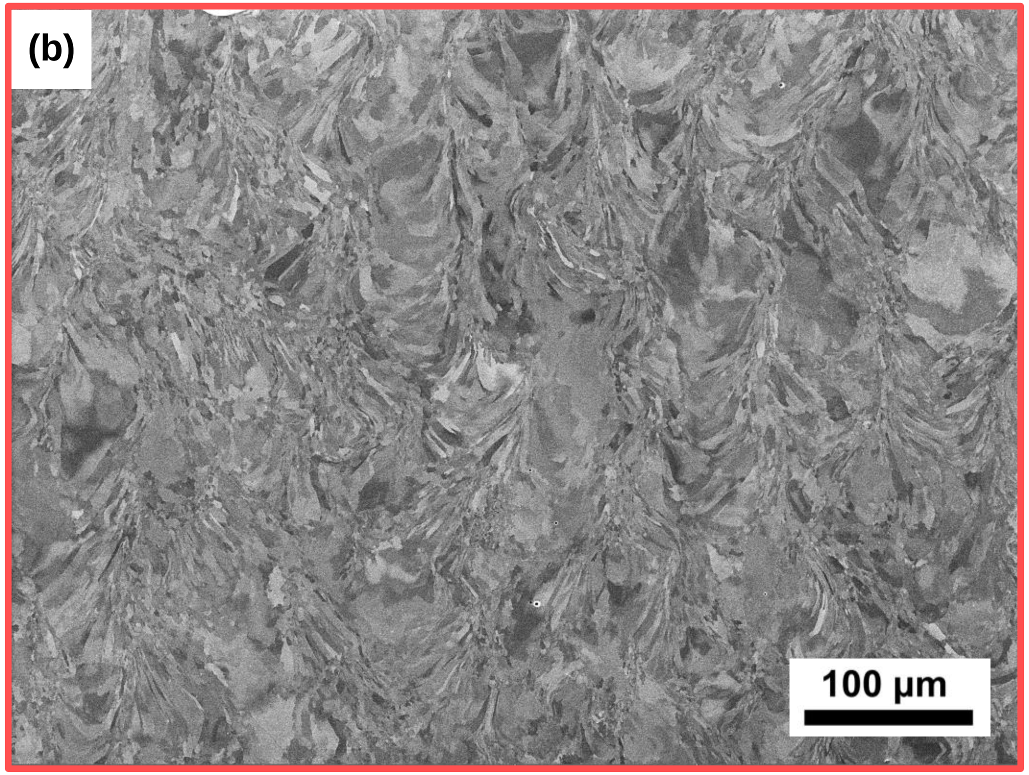
Material	Nb [wt%]	Hf [wt%]	Ti [wt%]	W [wt%]	Mo [wt%]	Zr [wt%]	O [ppm]	N [ppm]	C [ppm]
C103 Standard Spec. [8]	Bal.	*9 - 11*	*0.7 - 1.3*	< *0.5*	-	< *0.7*	< *250*	< *100*	< *150*
L-PBF **C103**	Bal.	9.85	0.92	0.27	-	-	425 ↑	58	19
NbW5-1 Standard Spec. [6]	Bal.	-	-	*4.5 – 5.5*	*1.7 – 2.3*	*0.7 – 1.2*	< *100*	< *100*	*500 - 1200*
L-PBF **Nb521**	Bal.	-	-	5.35	1.87	0.91	289 ↑	181 ↑	433 ↓

A dash symbolizes a result of “not reported/measured”

Microstructural Characterization: *L-PBF > Stress Relieved*

- Stress relieving teat treatment at 900 °C for 1-hour in high-vacuum (< 7E-4 Pa)



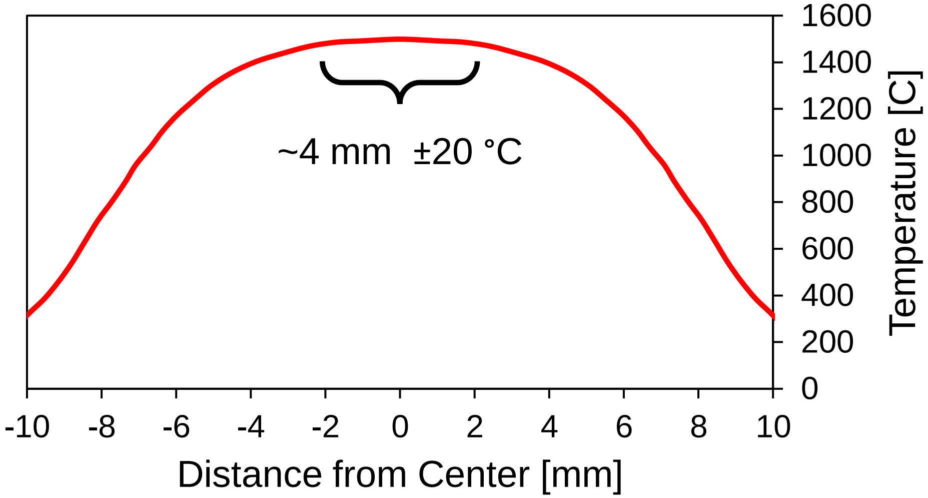


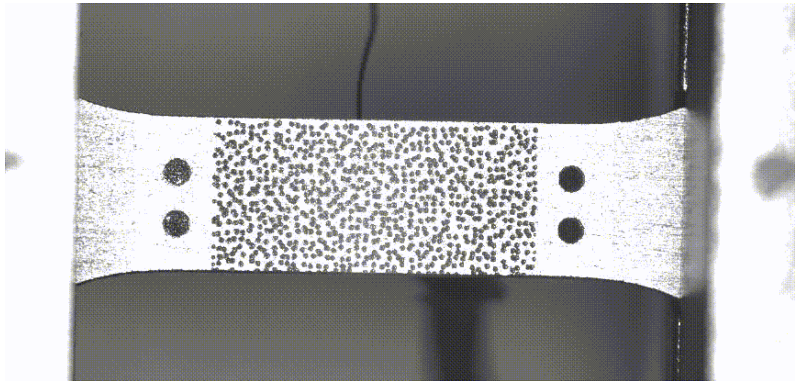
Secondary electron micrographs of the post stress relief L-PBF (a) **C103** and (b) **Nb521** materials

Elevated Temperature Mechanical Testing Equipment

- *Instron* Electro-Thermal Mechanical Testing (ETMT)
- Direct resistance heating (non-uniform thermal gradient)
- High-vacuum: < 10^{-5} Pa (< 10^{-7} Torr)
- Supports uniaxial tension & constant load (pseudo-creep)

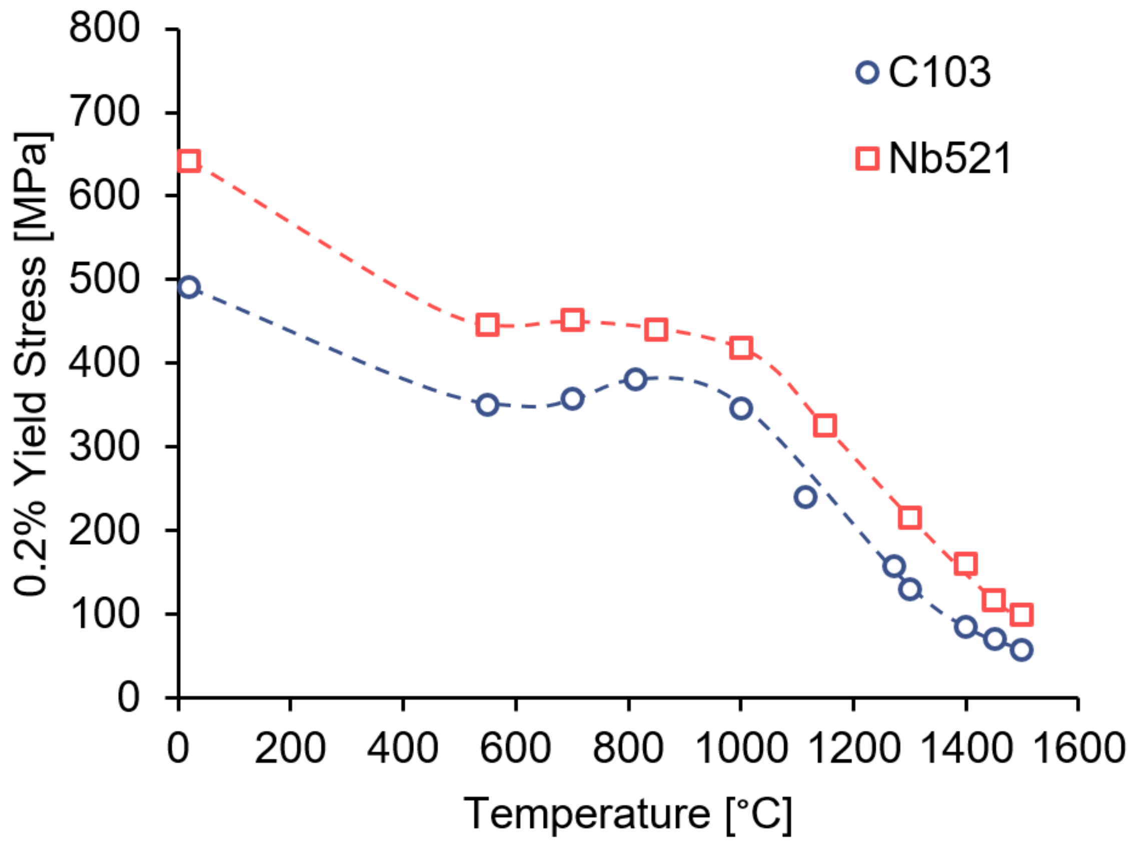
1500 °C Test Thermal Profile

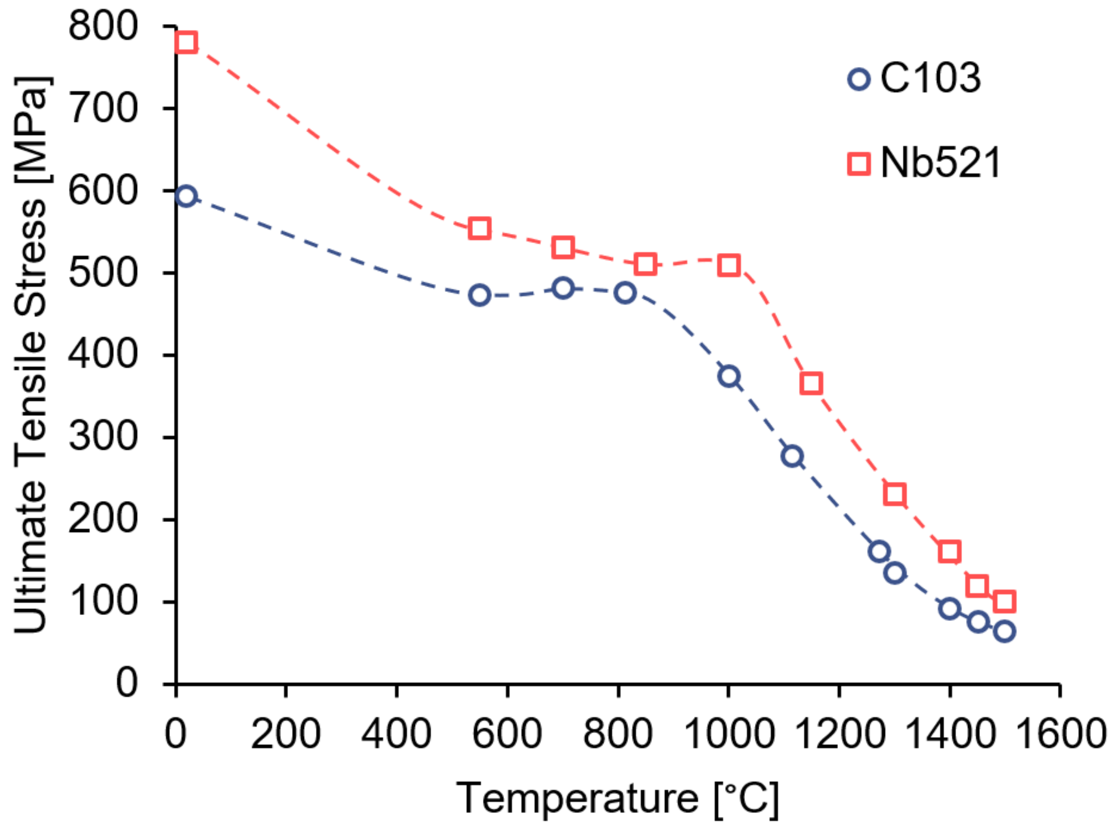




Elevated Temperature Uniaxial Tensile Testing

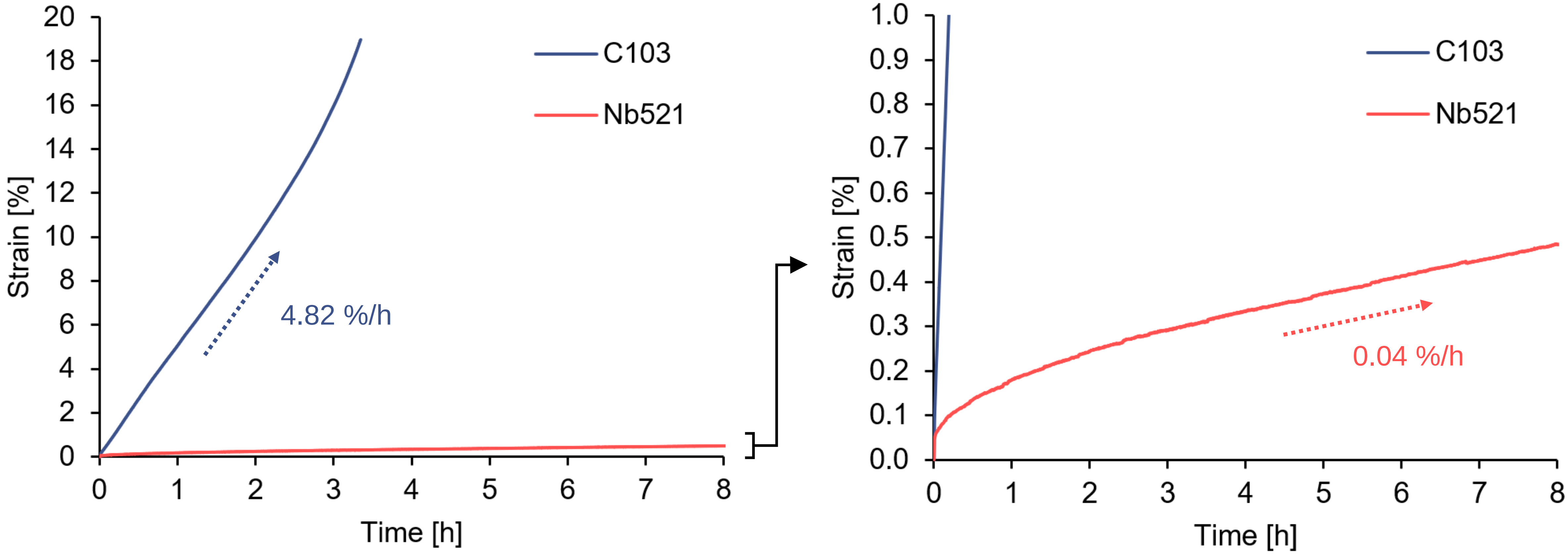
- **Nb521** has a ~70 MPa greater yield strength compared to **C103** across the entire examined temperature range.





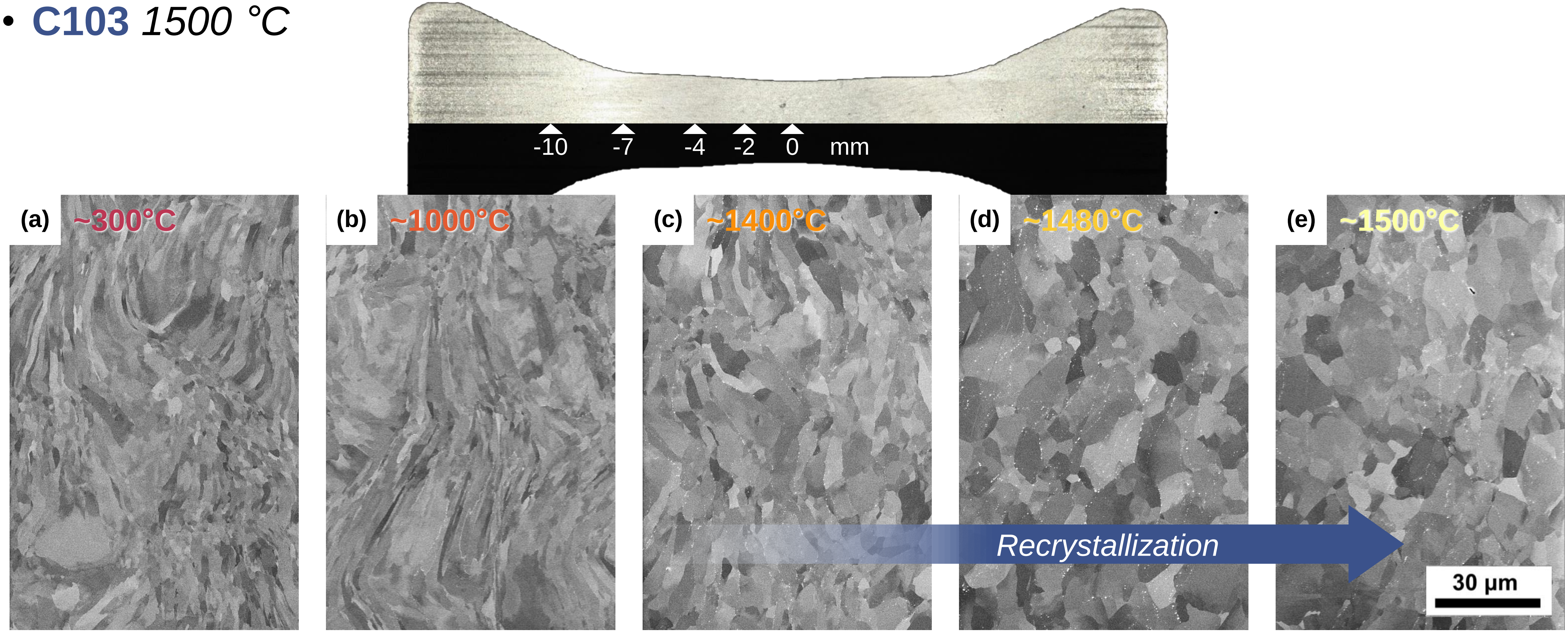
Elevated Temperature Constant Load (Pseudo-creep)

- At 1300 °C and a constant load of 50 MPa, **Nb521** has a creep rate nearly 2 orders of magnitude lower than **C103**.



Microstructural Characterization: *L-PBF > SR > Tension*

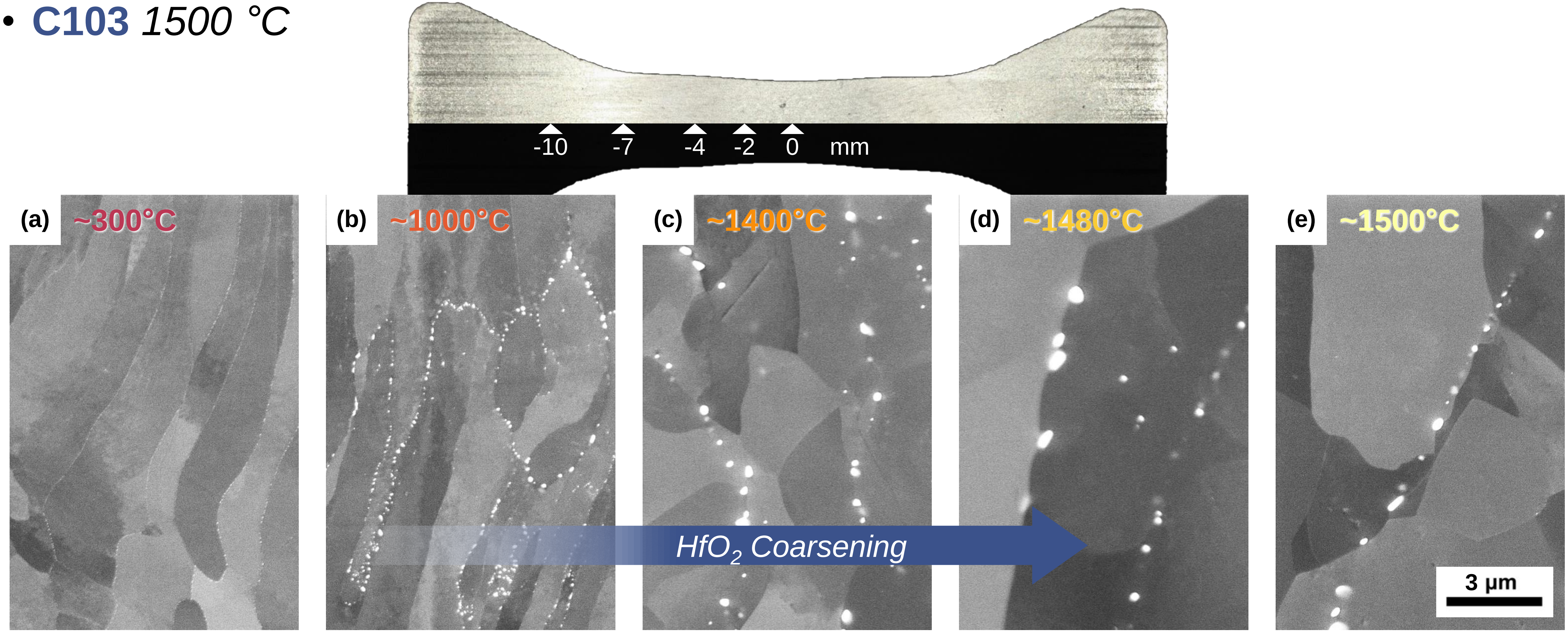
- **C103** *1500 °C*



Low magnification secondary electron micrographs of the 1500 °C elevated temperature L-PBF **C103** at (a) -10, (b) -7, (c) -4, (d) -2, and (e) 0 mm from central axis

Microstructural Characterization: *L-PBF > SR > Tension*

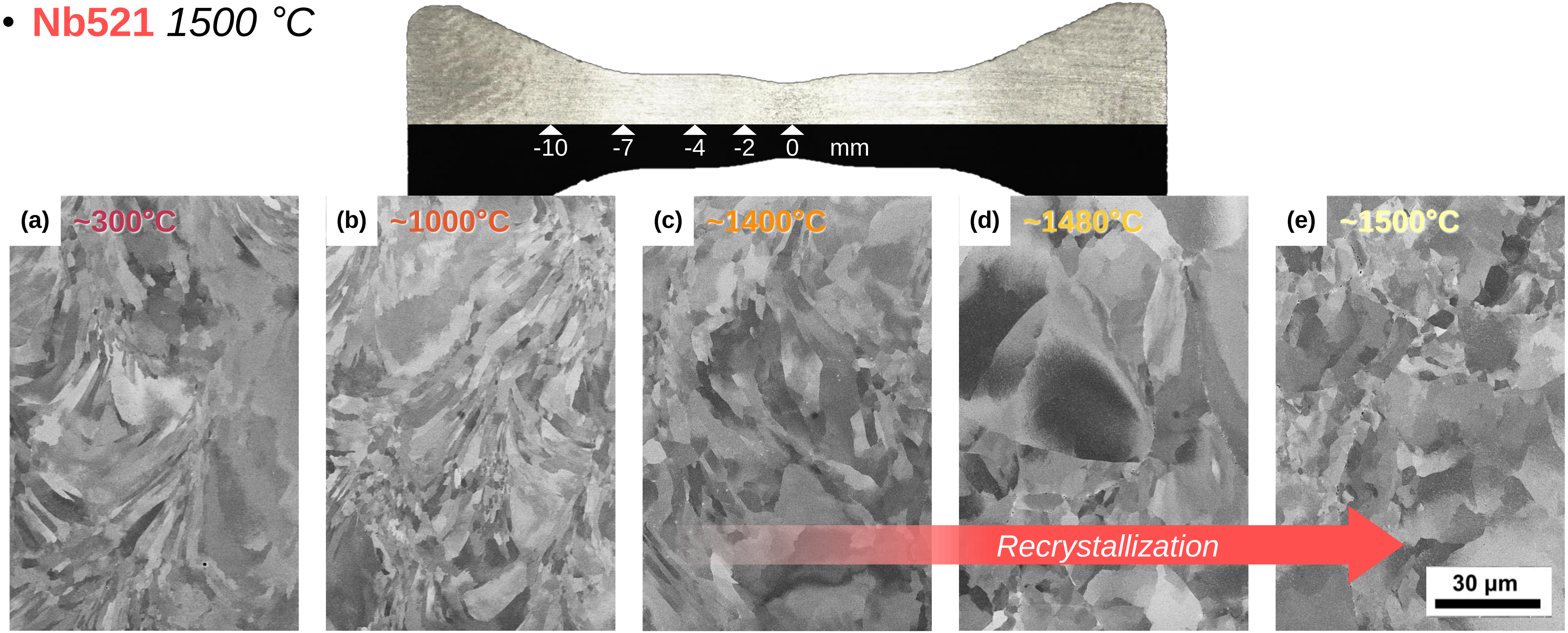
- **C103** *1500 °C*



High magnification secondary electron micrographs of the 1500 °C elevated temperature L-PBF **C103** at (a) -10, (b) -7, (c) -4, (d) -2, and (e) 0 mm from central axis

Microstructural Characterization: *L-PBF > SR > Tension*

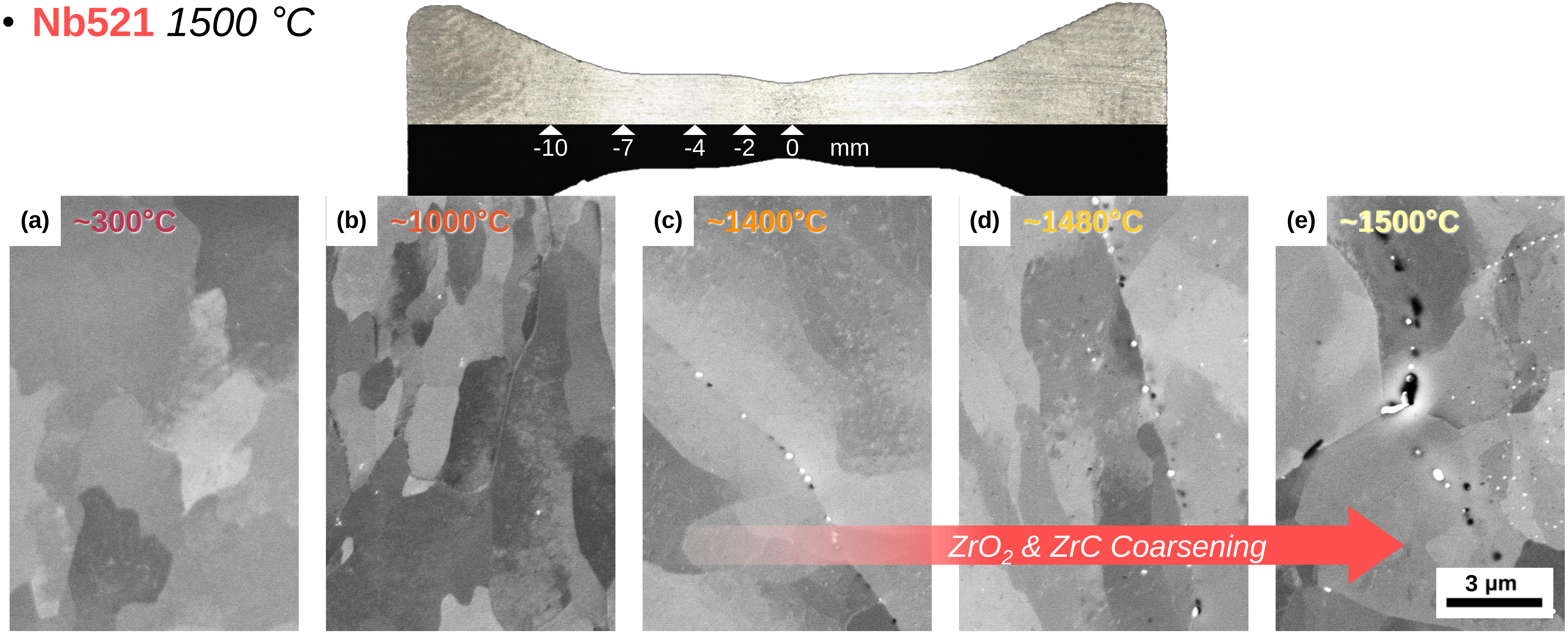
- **Nb521** *1500 °C*



Low magnification secondary electron micrographs of the 1500 °C elevated temperature L-PBF **Nb521** at (a) -10, (b) -7, (c) -4, (d) -2, and (e) 0 mm from central axis

Microstructural Characterization: *L-PBF > SR > Tension*

- **Nb521** *1500 °C*

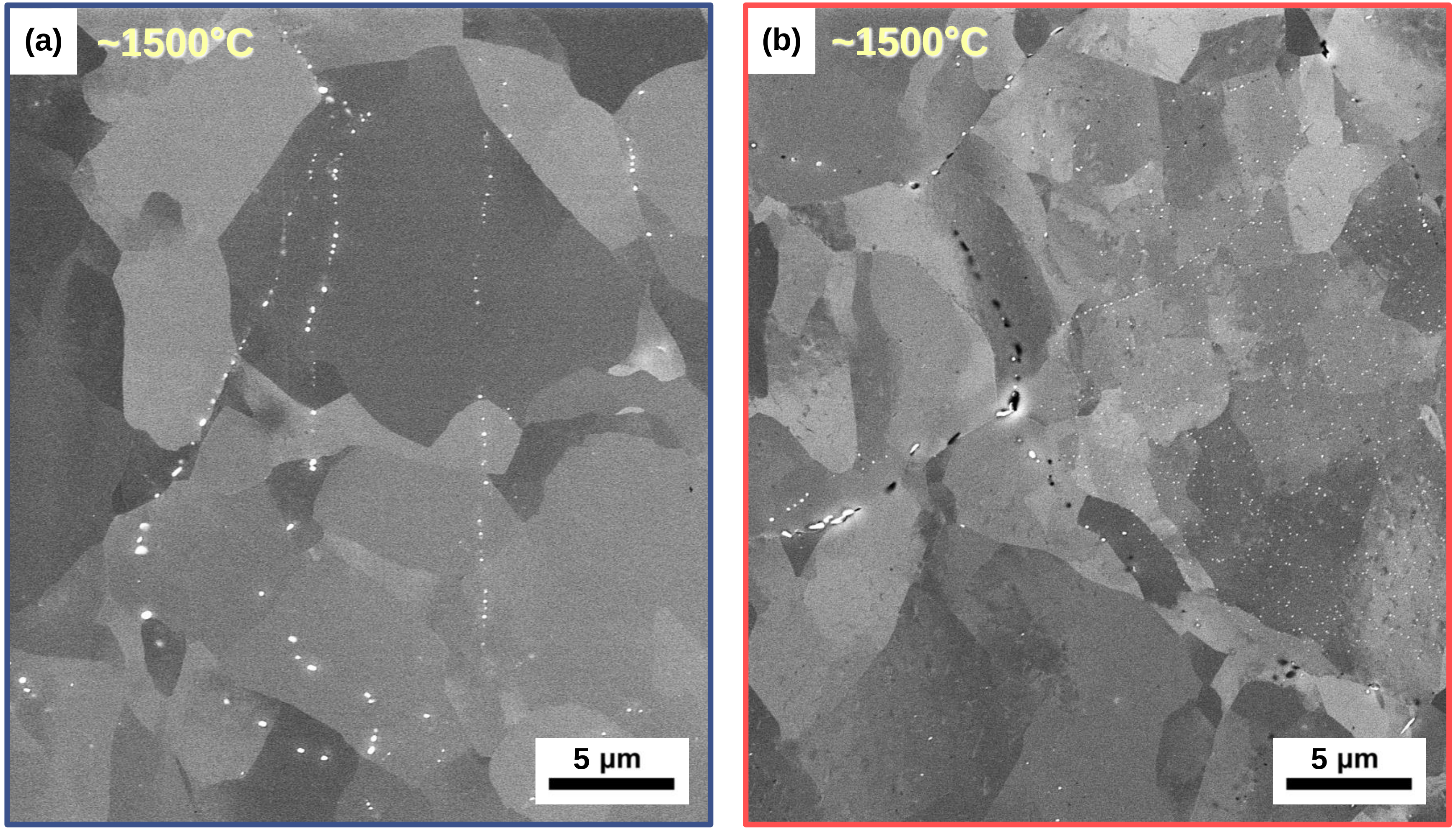


High magnification secondary electron micrographs of the 1500 °C elevated temperature L-PBF **Nb521** at (a) -10, (b) -7, (c) -4, (d) -2, and (e) 0 mm from central axis

Microstructural Characterization: *L-PBF > SR > Tension*

- **C103** vs. **Nb521** *1500 °C, 0 mm offset from central axis*

- **C103**'s hafnium-rich oxide precipitates were ineffective at pinning grain boundaries.
- **Nb521**'s zirconium-rich oxide and carbide precipitates were more often observed pinning boundaries and forming a fine dispersion within grains.



Secondary electron micrographs of the 1500 °C elevated temperature L-PBF (a) **C103** and (b) **Nb521** at 0 mm from central axis

Comparing Performance, Cost, and Other Properties

- Qualitatively, **C103** has an increased printability window.
- **C103** is only marginally less dense than **Nb521**.
- **Nb521** outperforms **C103** in elevated temperature strength, creep resistance, and maximum coated operating temperature.
- Despite the estimated raw material cost of **Nb521** being significantly lower, recent purchases of spherical powder for L-PBF have only shown only ~20% reduction in price per kg.

Metric	**L-PBF Materials**		
	C103		**Nb521**
Printability	Good	←	Fair
Density [g/cc]	8.81	⇦	8.84
Yield Strength at 1300 °C [MPa]	130	→	215
Pseudo-creep Rate at 1300 °C / 50 MPa [%/h]	4.82	→→	0.04
Estimated Raw Material Cost [USD/kg]	~$500	→	~$100
15-53 µm Spherical Powder Cost [USD/kg]	~$2,500	⇨	~$2,000
Typical Oxidation Coating	$NbSi_2$ (R512E)	→→	$MoSi_2$
Maximum Operating Temp. w/ Coating [C]	1400 °C		1600 °C

Conclusions

1. **Nb521** was successfully consolidated via the L-PBF process and achieved a relative density matching that of **C103** (99.96 and 99.92%, respectively). A slight increase in the volumetric energy density was required for **Nb521** L-PBF (138.9 vs 114.6 J/mm^3).
2. Elevated temperature tensile testing showed that **Nb521** has greater yield and ultimate tensile strengths compared to **C103** from room temperature up to 1500 °C. At temperatures above 1400 °C, **Nb521** had nearly double the strength of **C103**.
3. Constant load (50 MPa) tensile testing (pseudo-creep) at 1300 °C determined that **Nb521** is approximately 100X more creep resistant than **C103** with steady-state creep rates of 0.04 %/h and 4.82 %/h, respectively.
4. Microstructural analysis of the 1500 °C tension specimens showed both **Nb521** and **C103** experienced recrystallization and precipitate coarsening. However, the coarsened zirconium-rich precipitates in **Nb521** were more likely to be observed at grain boundaries indicating greater thermal stability.

References

1. N. Wang, H. Li, F. Xu, Z. Yin and X. Zhang, “Recent Development of Advanced Materials for Bipropellant Liquid Rocket Engine Thrust Chambers,” *Aerospace Materials and Technology*, 3, 2019.
2. L.J. Poinke and J.W. Davis, “Technical Assessment of Niobium Alloys Data Base for Fusion Reactor Applications,” *Technical Report C00-4247-2*, 1979.
3. J. Hebda, "Niobium Alloys and High Temperature Applications," Wah Chang - An Allegheny Technologies Company, Albany, 2001.
4. P.A. Kandarov, A.E. Kissil and G.G. Maksimovich, “Study of the Structure and Morphology of Strengthening Phases in 5VMTs Niobium Alloys at High Temperature,” *Metals*, 5, 1979.
5. C. Zhang, H. Lu, Z. Jia, D. Chen and G. Hu, “Application of Niobium-Tungsten Alloy Materials in Liquid Rocket Engine.” *Aerospace Materials and Technology*, 6, 2007.
6. J. Zhang, P. Wan, X. Wang and G. Zhao, “Formulation of National Military Standard for New Niobium-Tungsten Alloys,” *China Metal Bulletin*, Nov., 2015.
7. B. Zhu, X. Wu and M. Wan, “Research Progress of High Temperature Niobium Alloys for Aerospace Applications,” *The Chinese Journal of Nonferrous Metals*, 33, 2023.
8. ASTM International, B391-18 Standard Specification for Niobium and Niobium Alloy Ingots, West Conshohocken: *ASTM International*, 2018.
9. J. Chen et. al., “Strong and Ductile Niobium-based Refractory Alloy via Deformable Zirconia Nanoparticles,” *International Journal of Refractory Metals and Hard Materials*, 118, 2024.
10. Y. Sun et. al., “A Nb521 Alloy Processed by Selective Laser Melting: Microstructure and Tensile Properties,” *Vacuum*, 219, 2024.