Project 36H-L: Additive Manufacturing of Refractory Multi-Principal Element Alloys

Spring 2022 Semi-Annual Meeting

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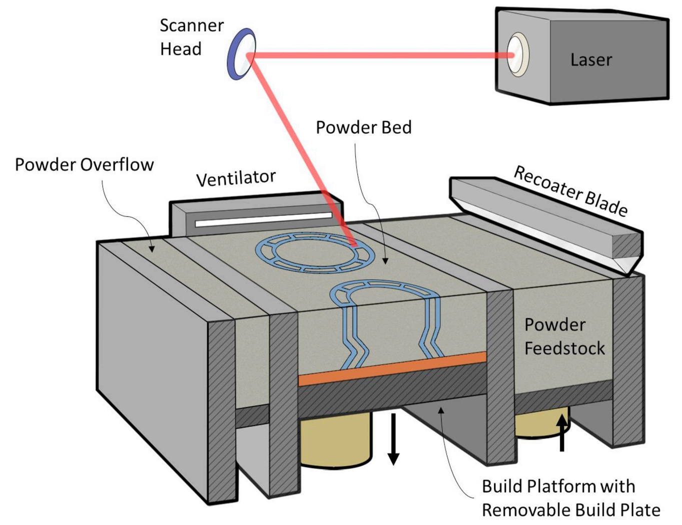
CANFSA – Center for Advanced Non-Ferrous Structural Alloys – An Industry/University Cooperative Research Center

Industrial Relevance:



L-PBF Process

P. Gradl, O. Mireles, N. Andrews, Introduction to Additive Manufacturing for Propulsion and Energy Systems, AIAA Propulsion and Energy Forum, 2021, DOI: 10.13140/RG.2.2.29815.55209

- Refractory multi-principal element alloys (RMPEAs) are a new class solid solution strengthened alloys
  - Include combinations of W, Mo, Ta, Nb, V, Hf, Zr, Re, Ti, Cr
  - Limited formability
- Additive manufacturing (AM) produces net-shape parts
  - Solves potential RMPEA thermomechanical processing issues
- Ultra-high temperature applications (> 1200 °C):
  - In-space propulsion
  - Reusable hypersonic wing leading edges for re-entry thermal protection
  - Fusion power and propulsion

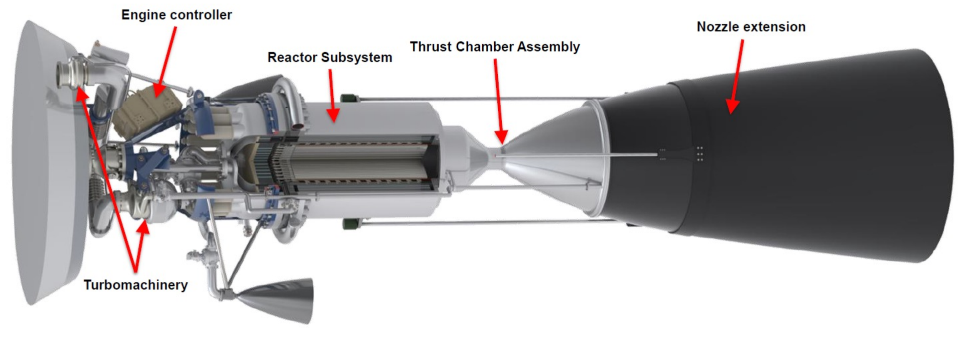


Diagram of nuclear thermal propulsion engine

Image courtesy of NASA GRC

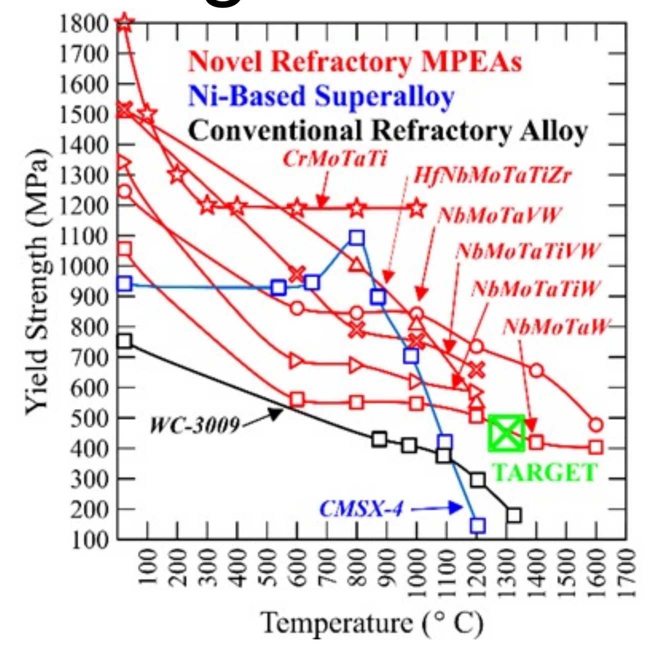
Procedures:

Modeling
- Thermo-Calc
- Ivantsov Marginal Stability
- Columnar-to-Equiaxed Transition (CET)
- Dendrite arm spacing

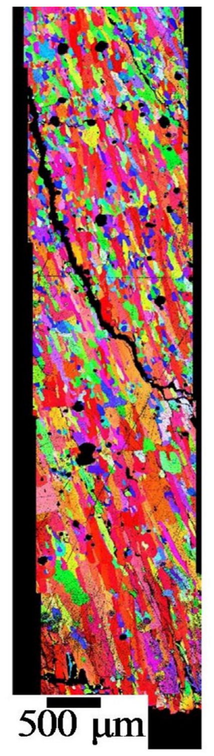
Experimental
- Single track laser melt
- SEM: solidification morphologies and dendrite arm spacings
- EDS: compositional variations
- EBSD: crystallographic orientations

Modeling + Experimental
- Compare results
- Identity discrepancies
- Iterate with new alloy formulations and modified solidification conditions

Background:



- RMPEAs afford promising properties at ultra-high temperatures
- (Left) Yield strength vs temperature for conventional alloys versus RMPEAs

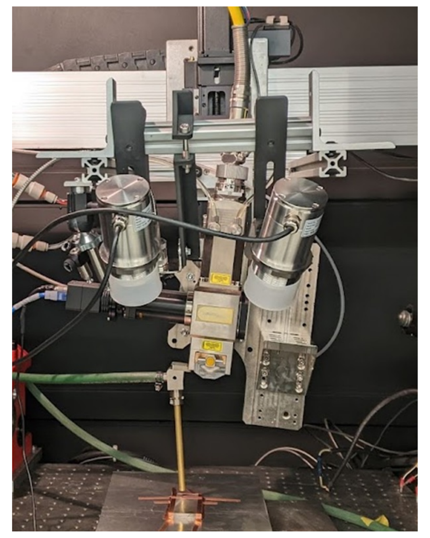


- (Left) Solidification cracking in laser-directed energy deposition (L-DED) MoNbTaW
- Compositional variation a challenge
- Further research required to mitigate

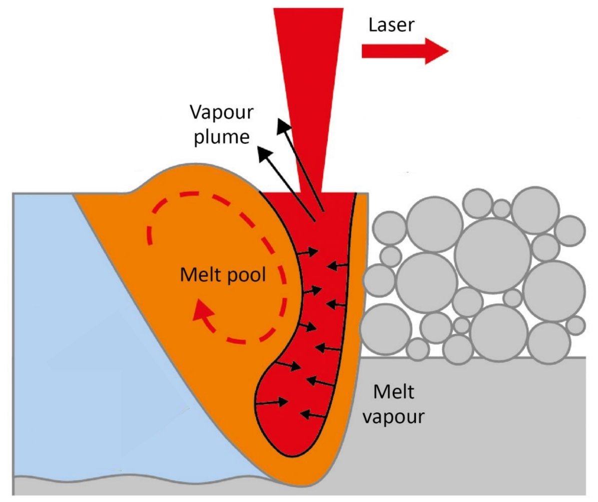
Melia et al., Melia et al., Applied Materials Today, 2020, 19:100560

O.N. Senkov et al., Intermetallics, 2011, 19:698-706
C.-C. Juan et al., Intermetallics, 2015, 62:76-83
Z.D. Han et al., Intermetallics, 2017, 84:153-157
F.G. Coury et al., Acta Materialia, 2019, 175:66-81
A. Sengupta et al., Journal of Materials Engineering and Performance, 1994, 3:73-82
C.C. Wojcik et al., Materials Research Society Symposium Proceedings, 1994, 322:519-530

Recent Progress:

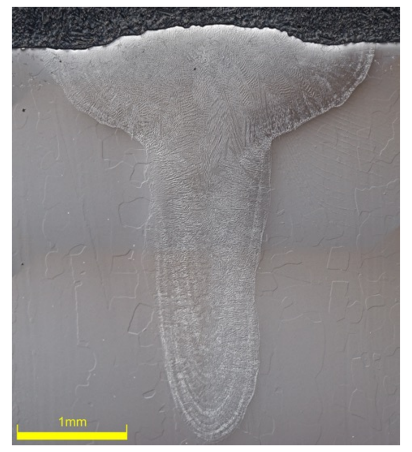


Interior of laser welding system at Mines

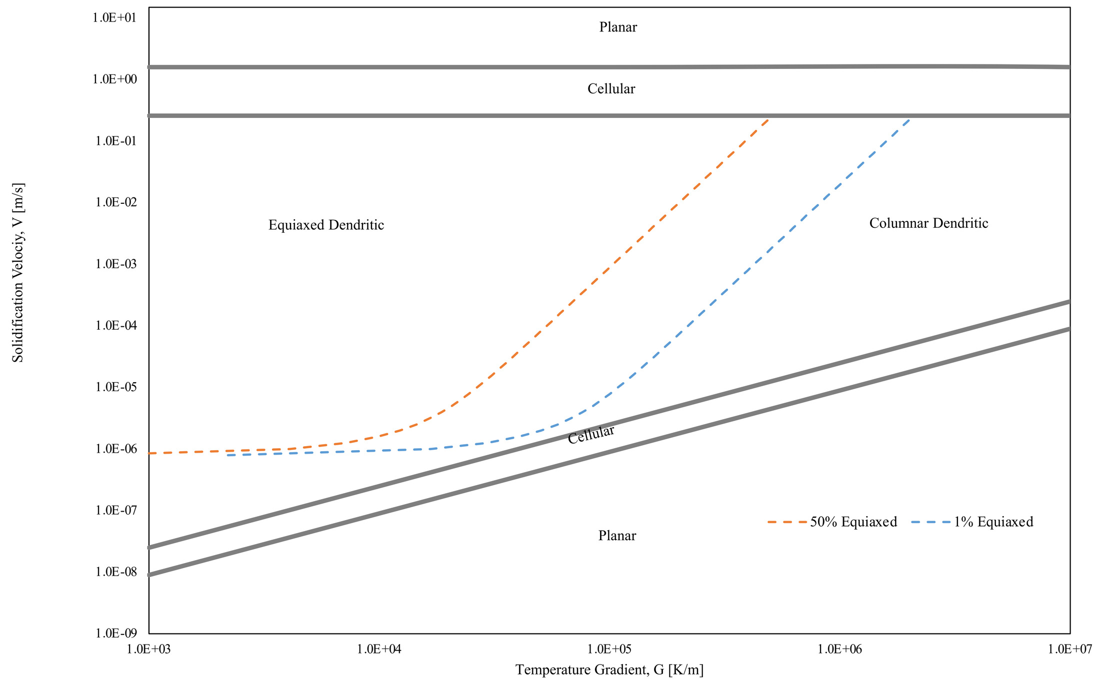


Keyhole mode melting in laser-powder bed fusion (L-PBF)

Adapted from metal-am.com



Nb-47Ti weld cross-section showing keyholing



G-V plot showing CET behavior of Nb-47Ti

AconityMINI L-PBF platform

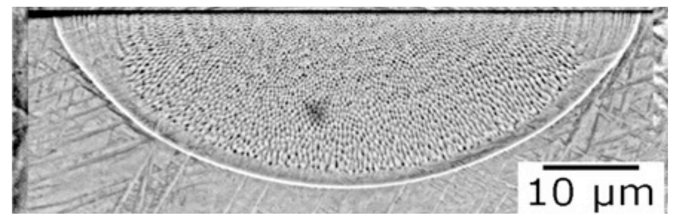
Future Work:

- Develop machine-appropriate laser track melt parameters
  - Avoid keyhole mode melting
- Gaümann modification of the Rosenthal solution for a Gaussian laser intensity profile

$$\Delta T[x,y,z] = \frac{2\alpha\beta P}{\kappa\pi^{3/2}} \cdot \int_0^\infty \frac{\exp\left[-2\frac{(x+V_b t)^2+y^2}{D_b^2+8\alpha t} - \frac{z^2}{4\alpha t}\right]}{\sqrt{\alpha t}\cdot(D_b^2+8\alpha t)} \cdot dt$$

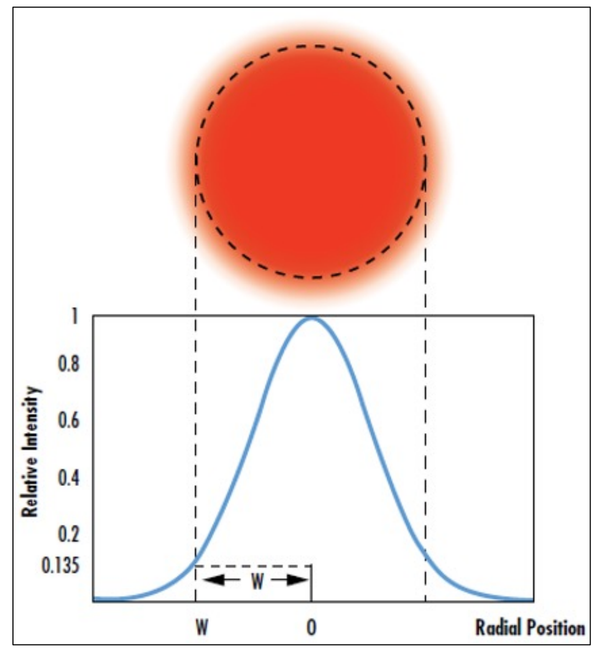
$$G[x,y,z] = \sqrt{G_x^2+G_y^2+G_z^2} \qquad G_{x,y,z} = \frac{\partial T}{\partial_{x,y,z}}$$

- Validate G-V model with EBSD
- Evaluate microsegregation in laser track melts of Nb-47Ti
- Evaluate relative extent of oxidation in Nb-47Ti track melts
- Produce equivalent evaluation of C103 solidification behavior



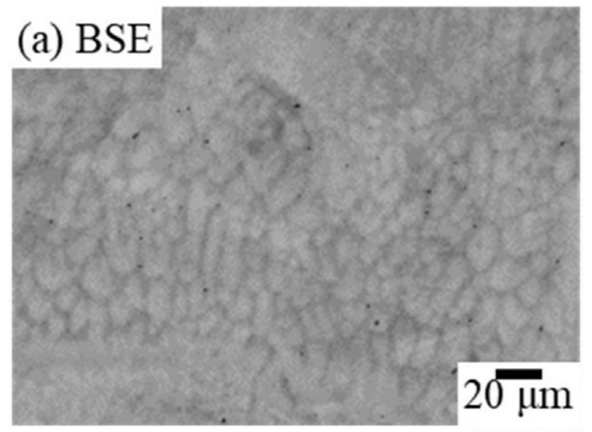
Conduction mode track melt.

J.D. Roehling et al., JOM, 2018, 70:1589-1597



Gaussian laser intensity profile.

Image courtesy of Edmund Optics



Microsegregation in $(MoTaW)_x(Nb)_{1-x}$.

Melia et al., Applied Materials Today, 2020, 19:100560

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