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

Project 49-L: Microstructure-strength relationships of heat-treated L-PBF Ti-5Al-5V-5Mo-3Cr

Semi-annual Spring Meeting
April 2022

- Student: Andrew Temple (ISU)
- Faculty: Dr. Peter Collins (ISU)
- Industrial Mentors:

Project 49-L: Microstructure-strength relationships of heat-treated L-PBF Ti-5Al-5V-5Mo-3Cr

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- Student: Andrew Temple (ISU)
- Advisor(s): Peter Collins (ISU)

Project Duration
PhD: January 2018 to May 2022

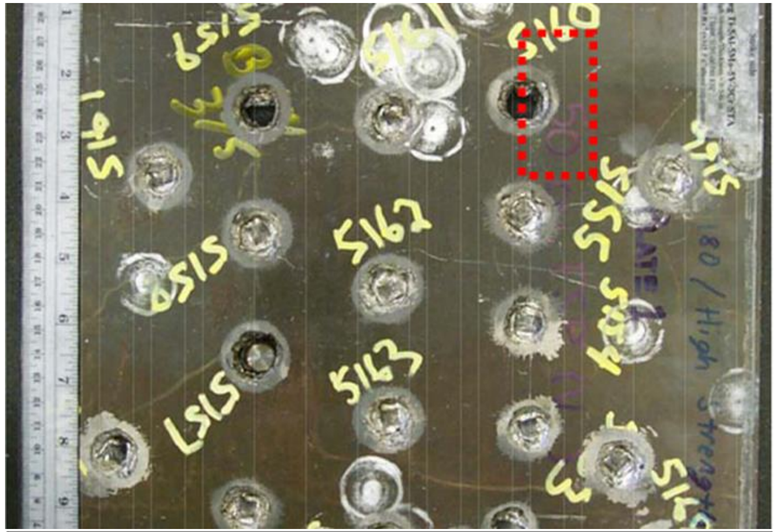
- Problem: Microstructure-property relationships of heat-treated additively manufactured beta titanium alloys are currently not well understood. Lack of quantitative microstructure-strength relationships.
- Objective: Develop and apply a predictive yield strength equation to obtain an in-depth understanding of microstructure-strength relationships in L-PBF Ti-5553.
- Benefit: The understanding of microstructure-property relationships as they relate to heat-treated L-PBF Ti-5553. Enable future alloy and process design/development.

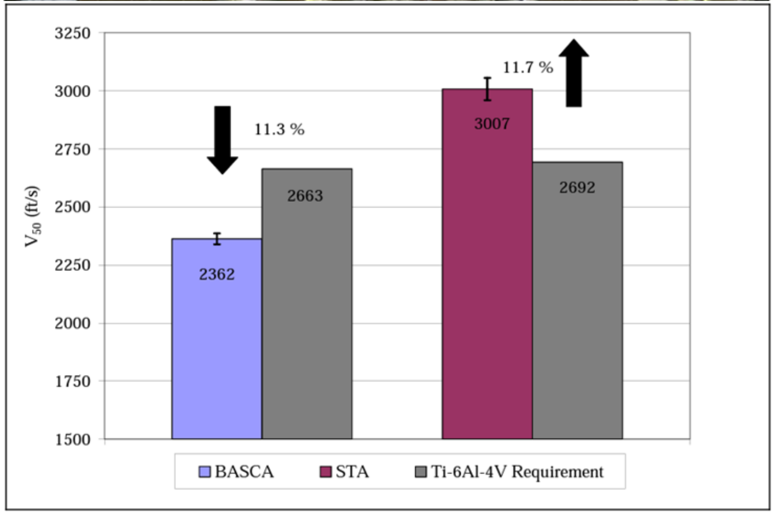
Recent Progress

- Presentation at TMS 2022
- Applied for graduation
- Dissertation draft 90% complete
- PhD final oral examination scheduled for Thursday, April 28

Metrics		
Description	**% Complete**	**Status**
1. Literature review	95%	●
2. Gleeble heat treatment	100%	●
3. Tensile testing	100%	●
4. SEM characterization and microstructural quantification	100%	●
5. Model development, application, and assessment of limitations	90%	●

Industrial Relevance





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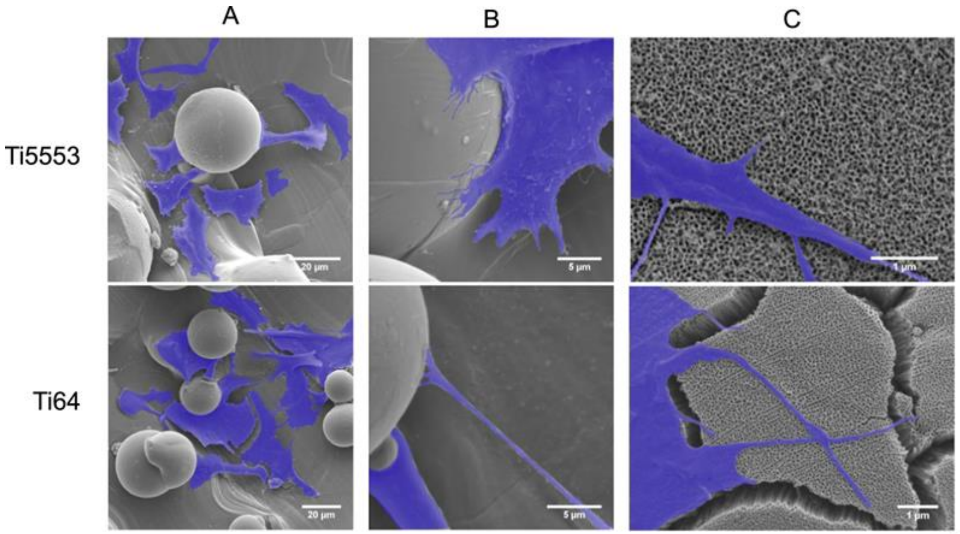
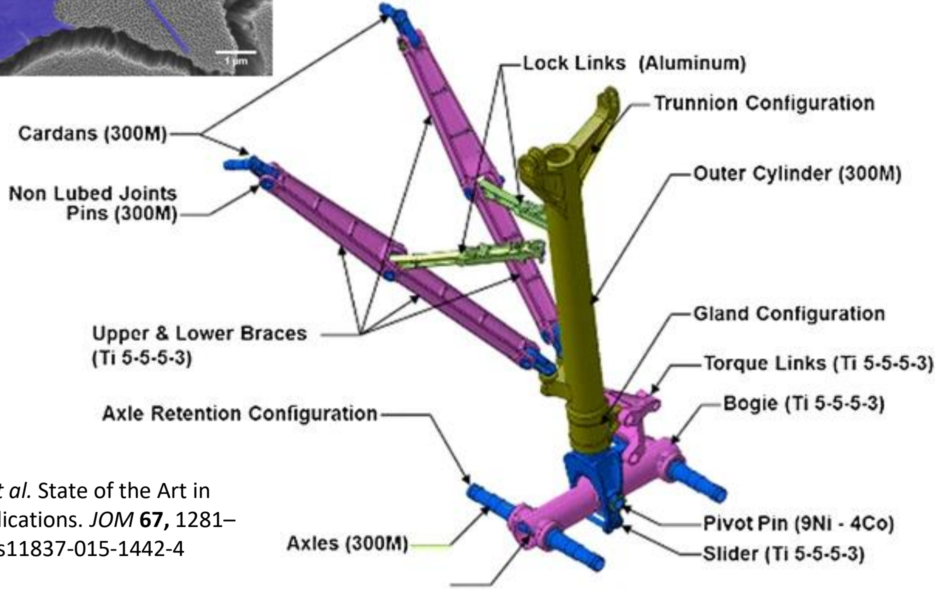
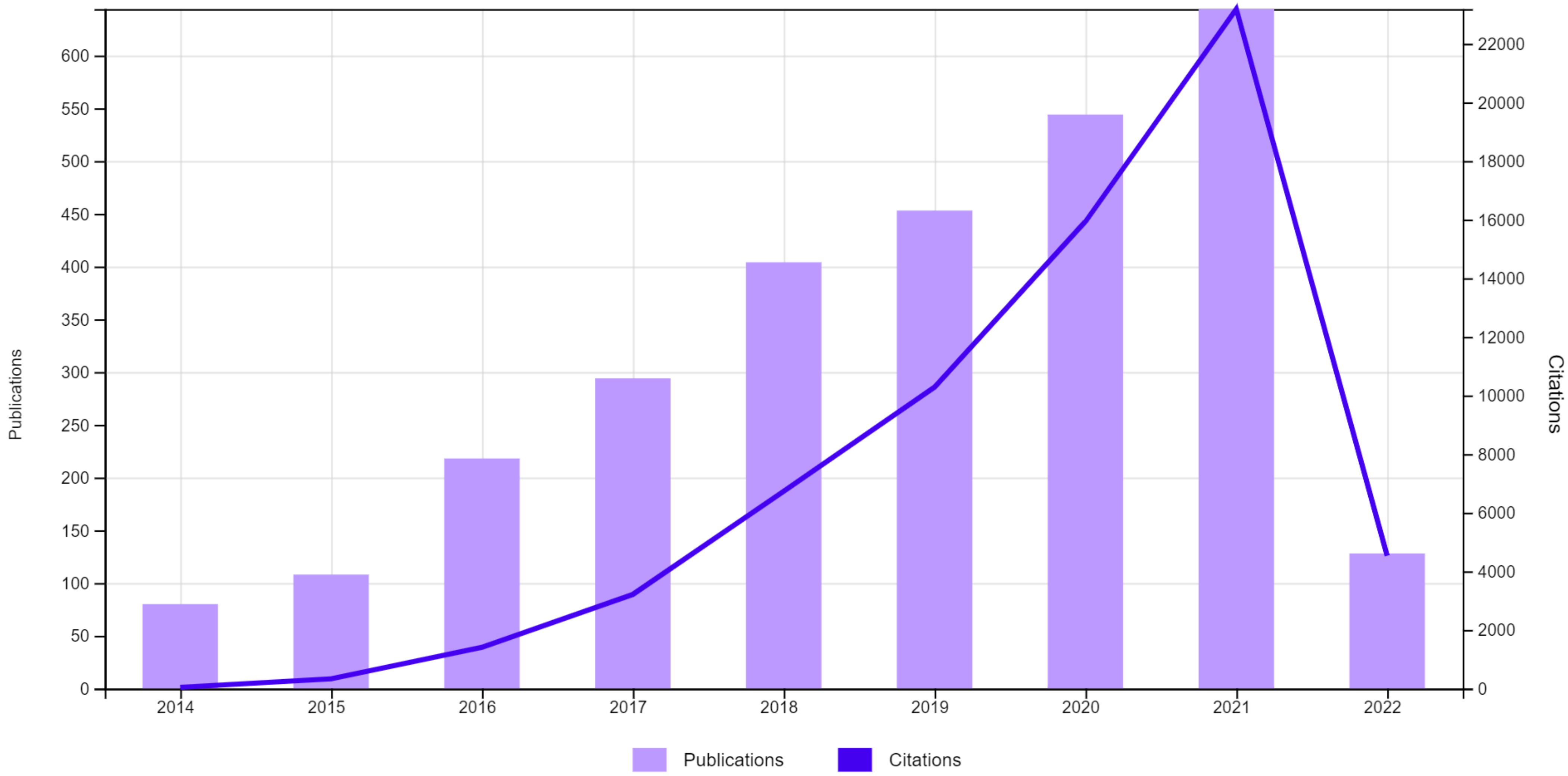


C. Micheletti *et al.*, Ti-5Al-5Mo-5V-3Cr bone implants with dual-scale topography: A promising alternative to Ti-6Al-4V. *Nanotechnology*. 31 (2020), doi:10.1088/1361-6528/ab79ac.

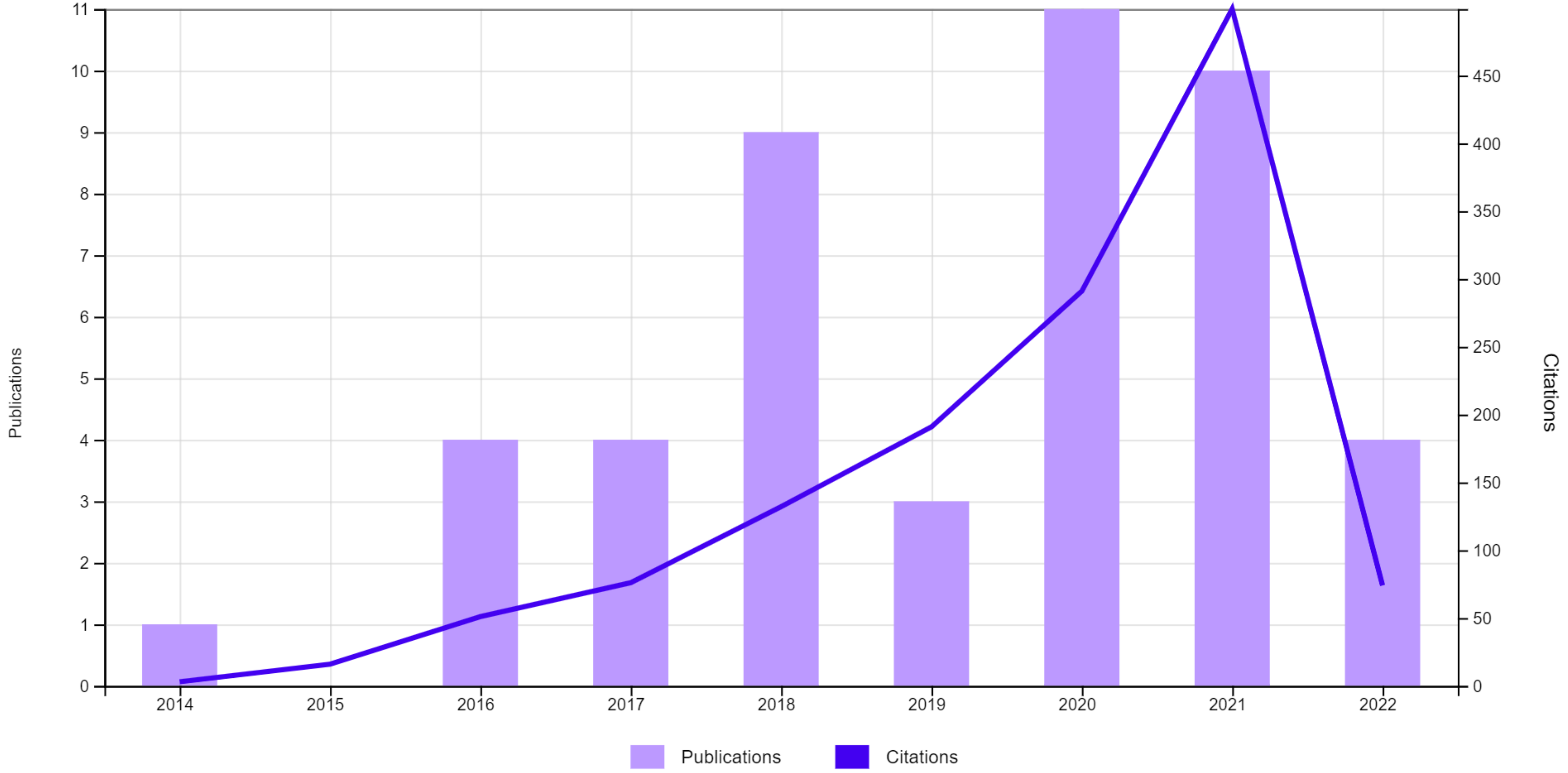


Cotton, J.D., Briggs, R.D., Boyer, R.R. *et al.* State of the Art in Beta Titanium Alloys for Airframe Applications. *JOM* **67,** 1281–1303 (2015). https://doi.org/10.1007/s11837-015-1442-4

"Titanium" & "Additive manufacturing"



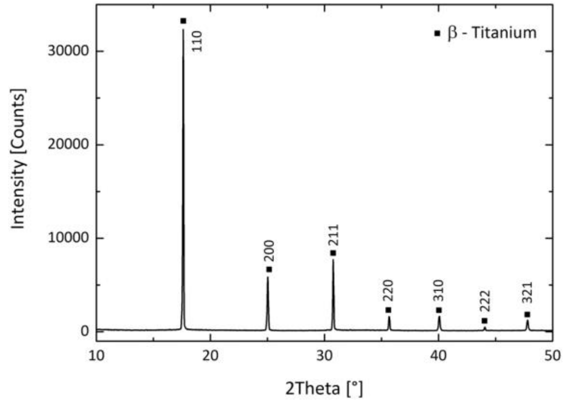
“Beta titanium” & “Additive manufacturing”



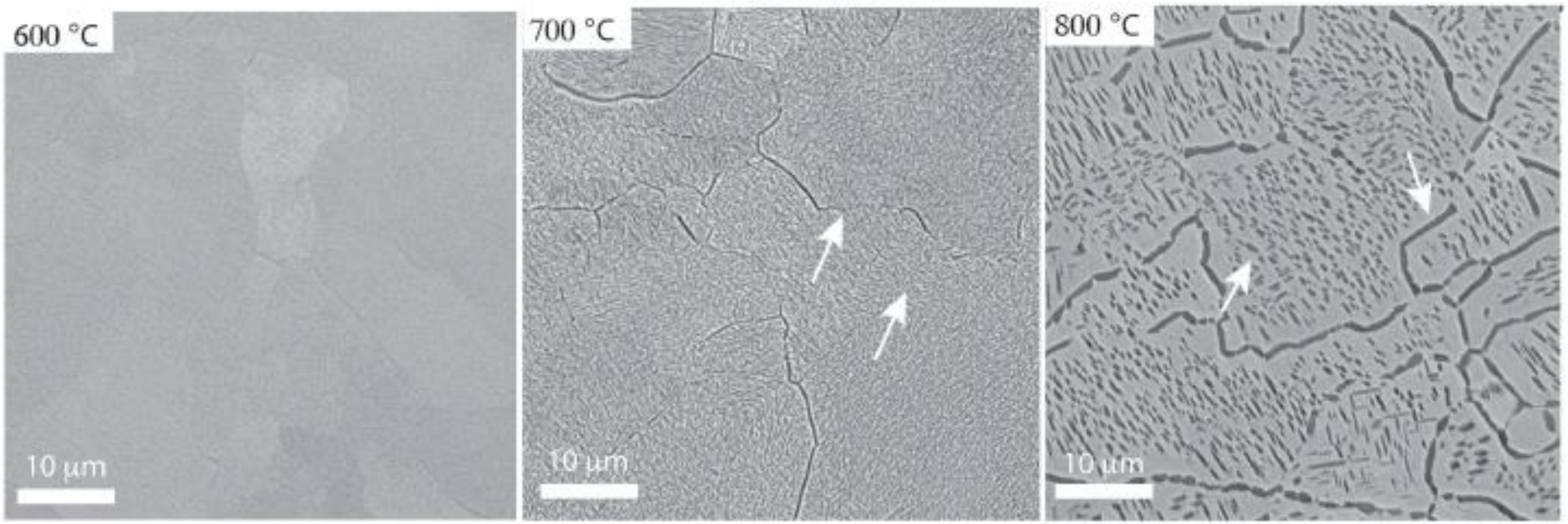
Motivation

Why Ti-5553?
- Low density
- High strength
- Two-phase alloy (50/50)
- Wide range of properties

Why AM?
- Difficult to machine
- Cost savings
- Complex structures/geometries
- Single-phase as-built

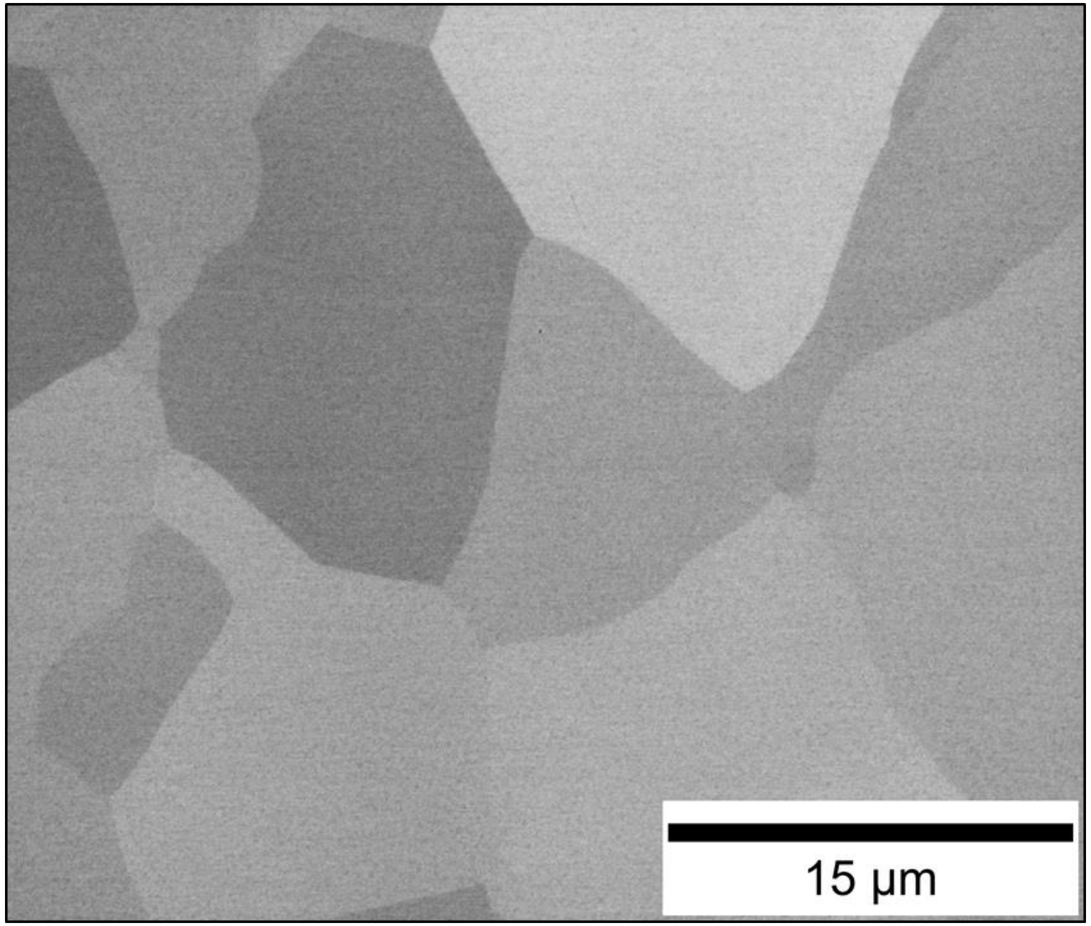


H. Schwab, F. Palm, U. Kühn, J. Eckert, Microstructure and mechanical properties of the near-beta titanium alloy Ti-5553 processed by selective laser melting. *Materials and Design*. 105, 75–80 (2016).

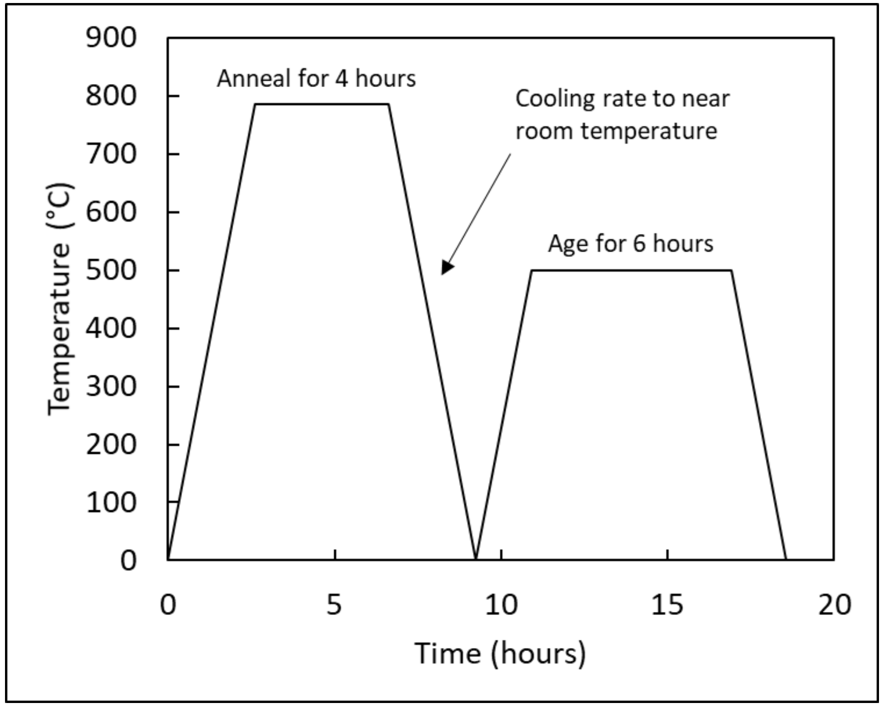


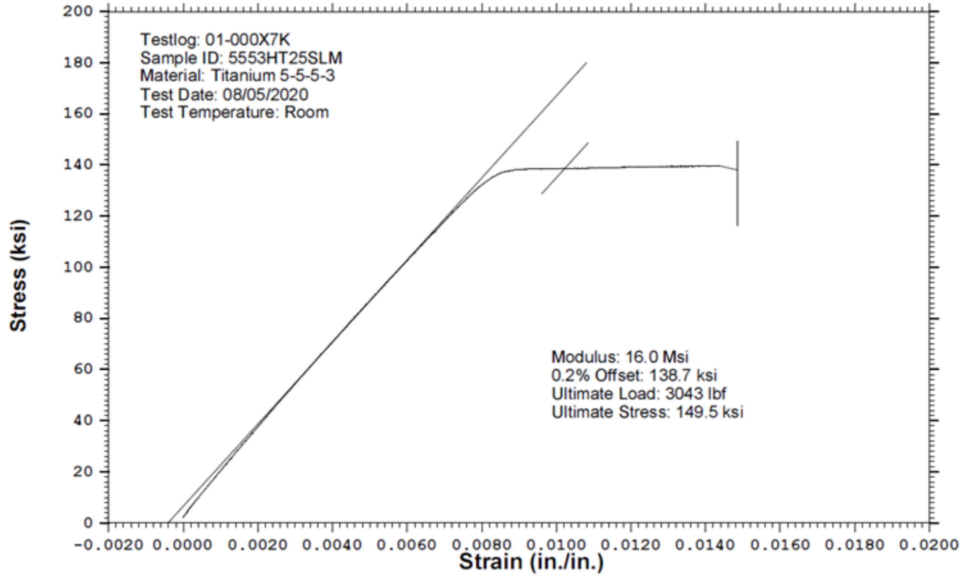
H. D. Carlton, K. D. Klein, J. W. Elmer, Evolution of microstructure and mechanical properties of selective laser melted Ti-5Al-5V-5Mo-3Cr after heat treatments. Science and Technology of Welding and Joining. 24, 465–473 (2019).

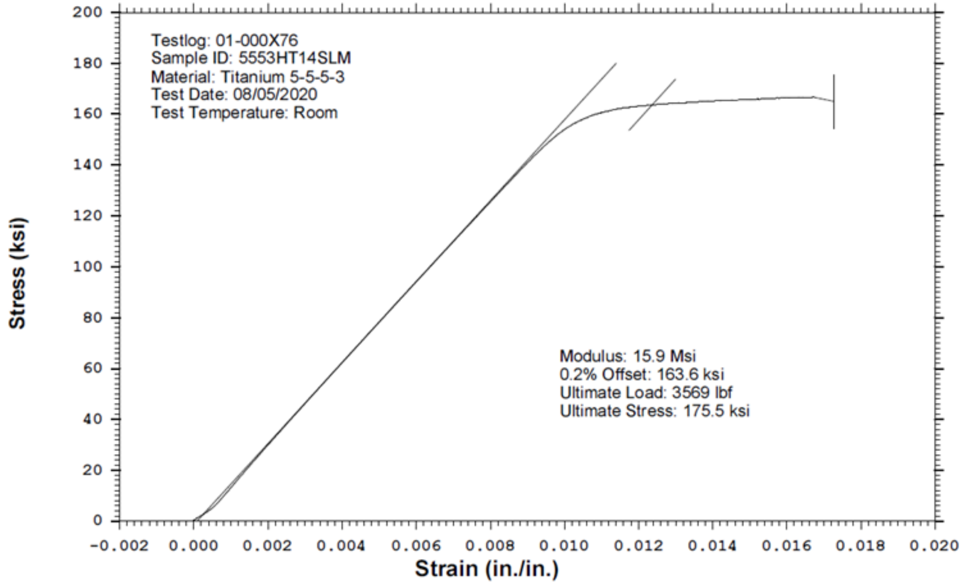
L-PBF Ti-5Al-5V-Mo-3Cr heat treatments

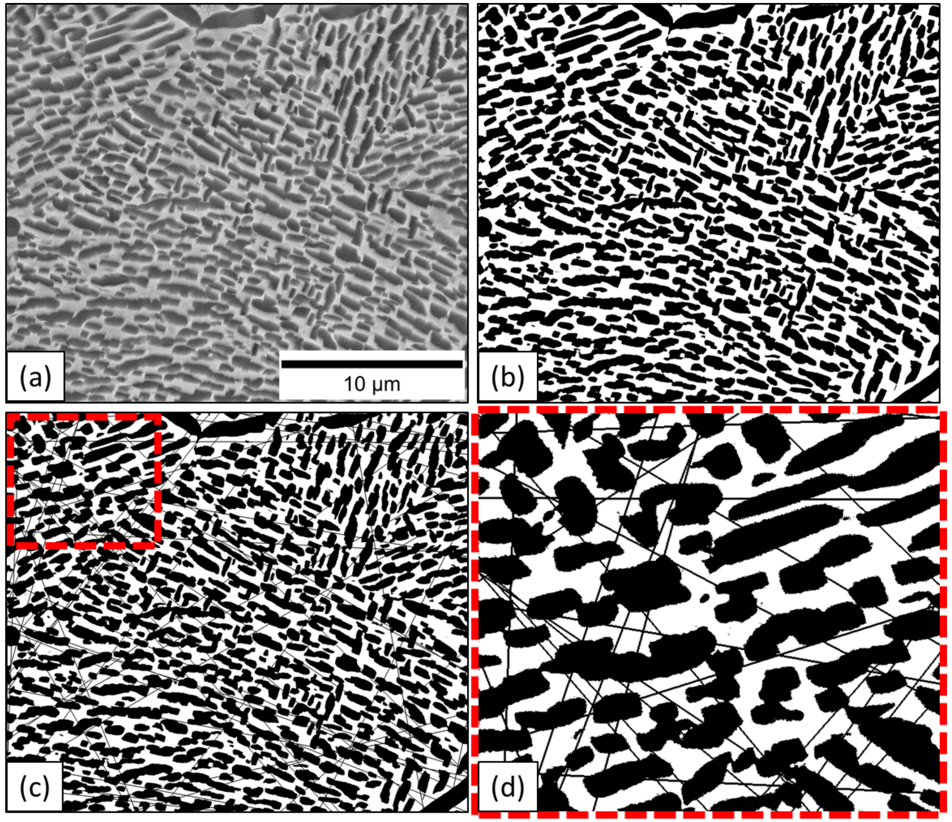


Variables	Levels		
	Low	Mid	High
Annealing temperature (°C)	700	745	785
Cooling rate (°C/min)	5	50	500
Aging temperature (°C)	500	575	650

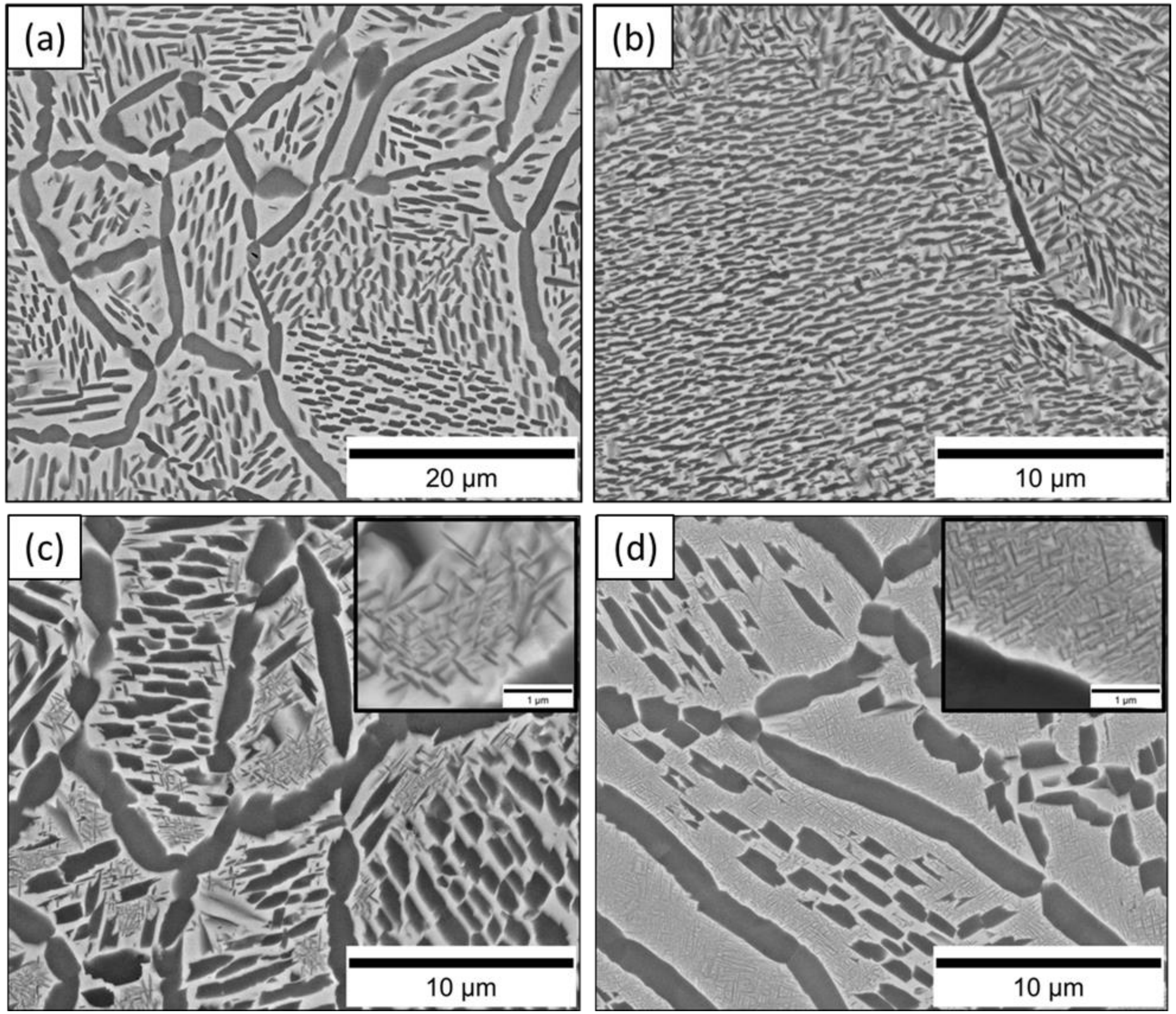


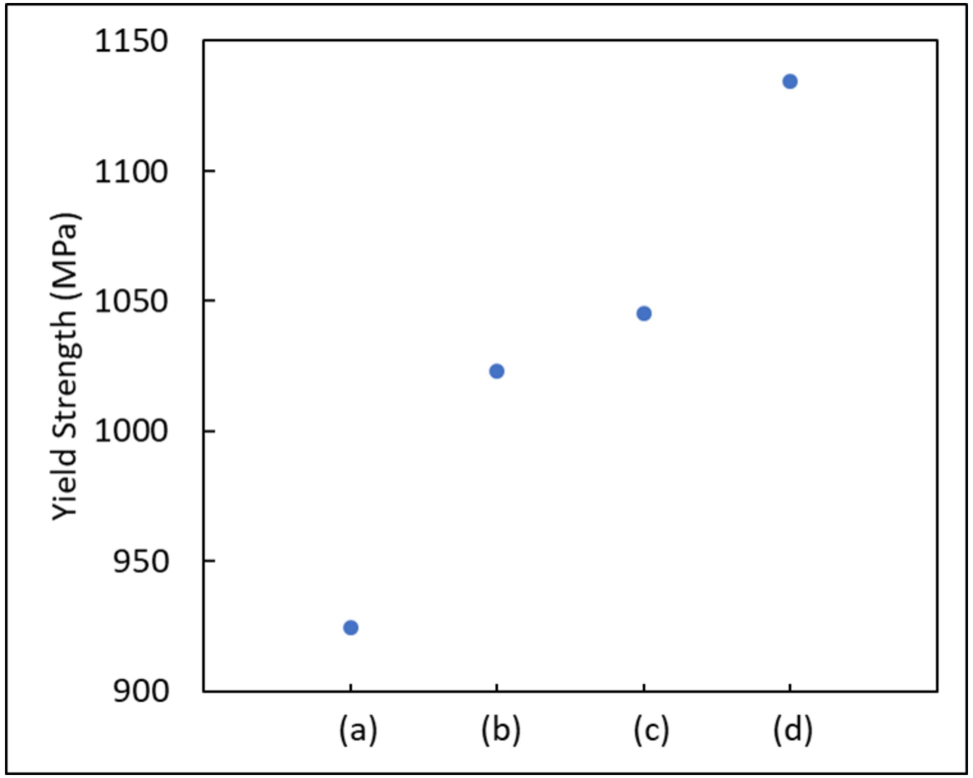




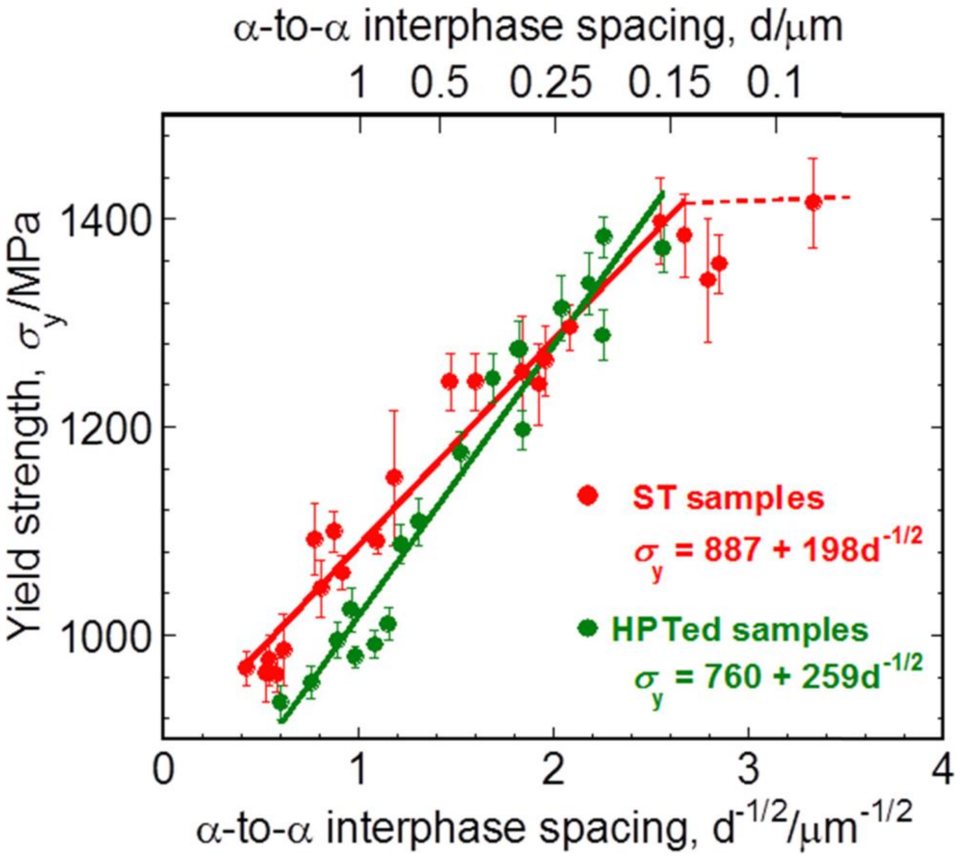


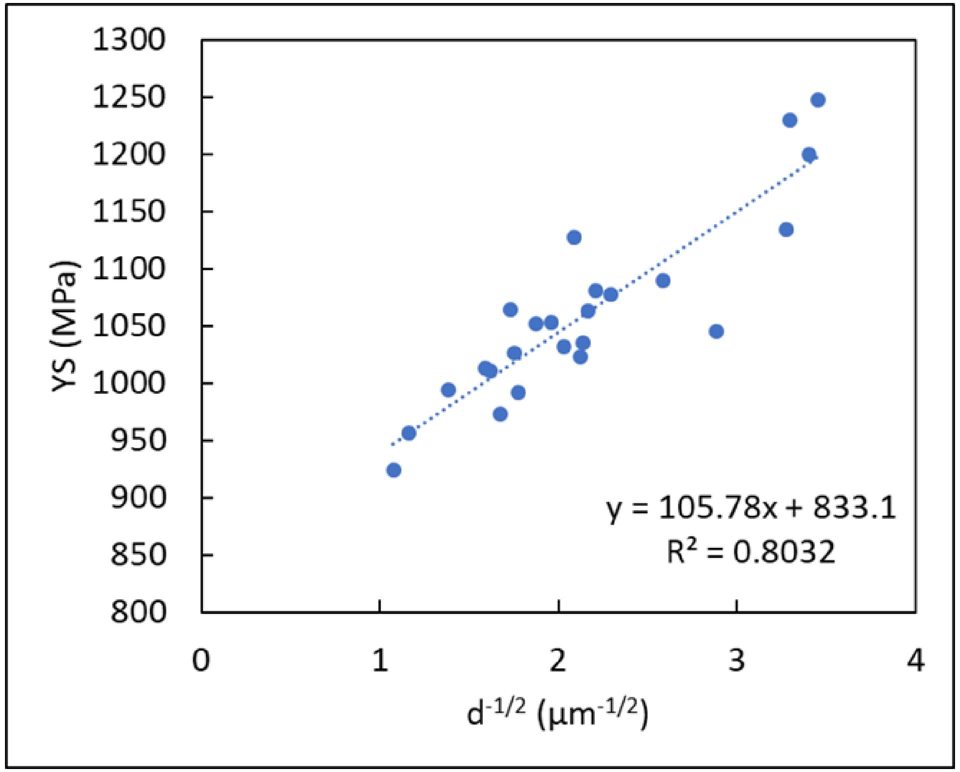
	α Phase Fraction (%)	α-to-α Distance (μm)	0.2%YS (MPa)
Average	47.17	0.4288	1098
Max	58.13	1.147	1468
Min	25.82	0.1767	925


(a)
20 μm
(b)
10 μm
(c)
1 μm
10 μm
(d)
1 μm
10 μm

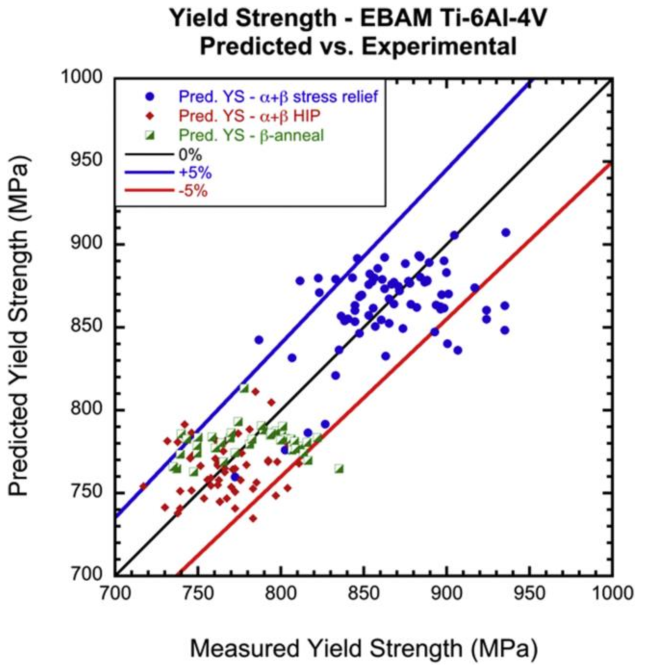

Yield Strength (MPa)
1150
1100
1050
1000
950
900
(a)
(b)
(c)
(d)

Hall-Petch Strengthening



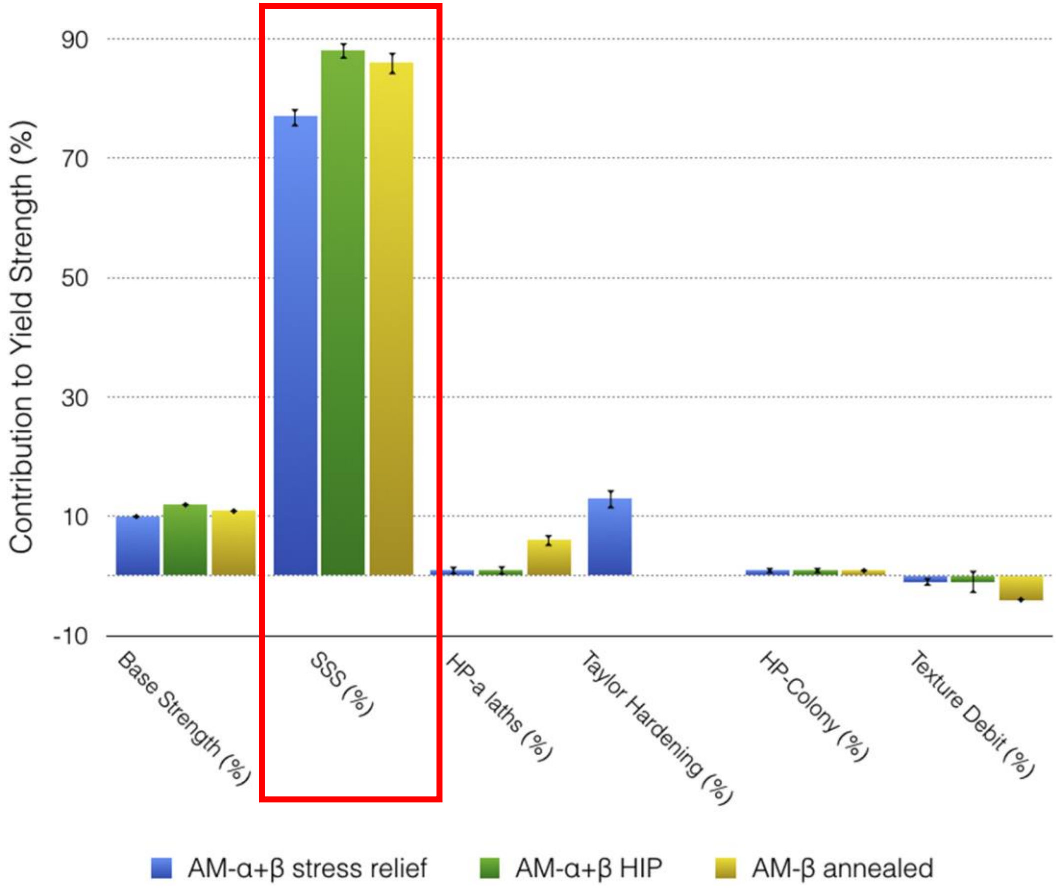


B. Jiang, S. Emura, K. Tsuchiya, Microstructural evolution and its effect on the mechanical behavior of Ti-5Al-5Mo-5V-3Cr alloy during aging. Materials Science and Engineering A. 731, 239–248 (2018).



$$\sigma_{ys} = \begin{cases} F_V^{\alpha} \cdot \sigma_O^{\alpha} + F_V^{\beta} \cdot \sigma_O^{\beta} + & \text{Intrinsic Strength} \\ F_V^{\alpha} \cdot \sigma_{SS}^{\alpha} + F_V^{\beta} \cdot \sigma_{SS}^{\beta} + & \text{Solid Solution Strengthening} \\ F_V^{col} \cdot C_{\alpha-lath} \cdot (t_{\alpha-lath})^{n} \cdot (t_{\beta-rib})^{-n} + & \text{Hall -- Petch Strengthening (alpha laths)} \\ F_V^{col} \cdot C_{col} \cdot (t_{colony})^{n} + & \text{Hall -- Petch Strengthening (colonies)} \\ (-1) \cdot (AxisDebit) + & \text{Texture Debits (easier slip)} \\ F_V^{BW} \cdot \alpha M G b \sqrt{\rho} & \text{Taylor Hardening} \end{cases}$$

$$\sigma_{ys} = \begin{cases} F_V^{\alpha} \cdot 89 + F_V^{\beta} \cdot 45 + \\ F_V^{\alpha} \cdot \left(149 \cdot x_{Al}^{0.667} + 759 \cdot x_O^{0.667}\right) + F_V^{\beta} \cdot \left(\left(22 \cdot x_V^{0.7}\right)^{0.5} + \left(235 \cdot x_{Fe}^{0.7}\right)^{0.5}\right)^2 + \\ F_V^{col} \cdot 150 \cdot (t_{\alpha-lath})^{-0.5} \cdot (t_{\beta-rib})^{0.5} + \\ F_V^{col} \cdot 125 \cdot (t_{colony})^{-0.5} + \\ (-1) \cdot (AxisDebit) + \\ F_V^{BW} \cdot \alpha M G b \sqrt{\rho} \end{cases}$$



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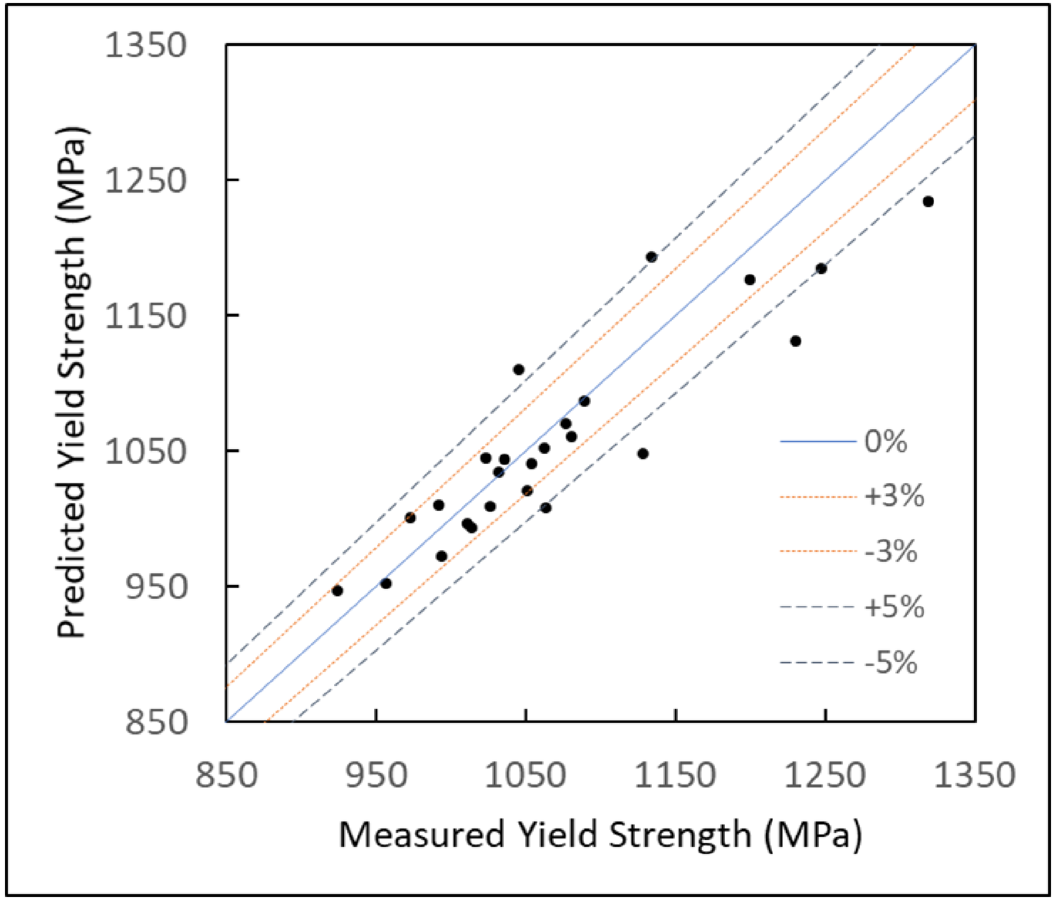

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$$YS = F_V^{\alpha} \cdot (149 \cdot x_{Al}^{0.667} + 740 \cdot x_O^{0.667}) \qquad (\alpha \text{ solid solution})$$

$$+F_V^{\beta} \cdot ((22 \cdot x_V^{0.7})^{0.5} + (247 \cdot x_{Cr}^{0.7})^{0.5})^2 \qquad (\beta \text{ solid solution})$$

$$+F_V^{\alpha} \cdot 210 \cdot d^{-1/2} \qquad (\text{inter-lath Hall-Petch})$$

Lattice parameters versus solute content curves

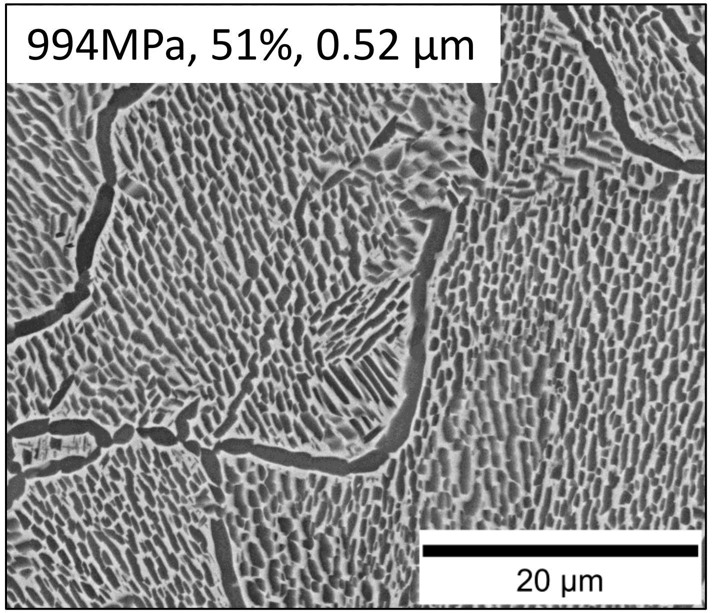
Greater slope ∝ greater size misfit (qualitative)

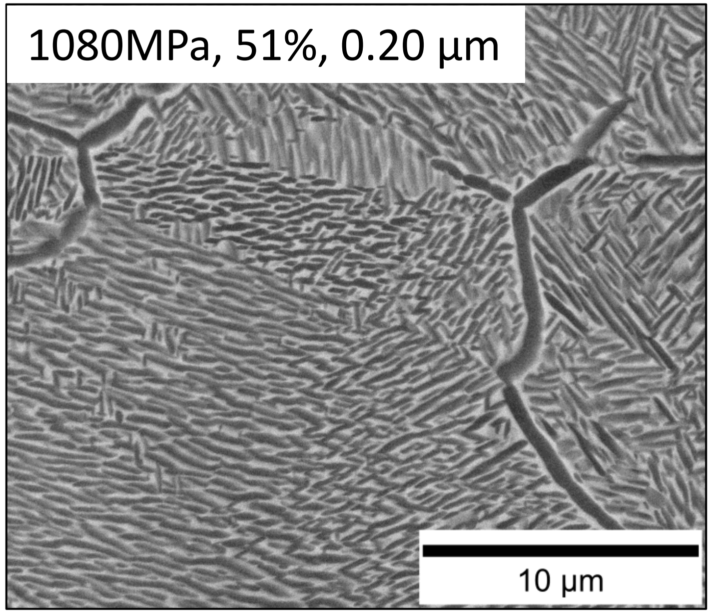
$$\sigma_{SS}^{Cr} > \sigma_{SS}^{V} > \sigma_{SS}^{Mo}$$

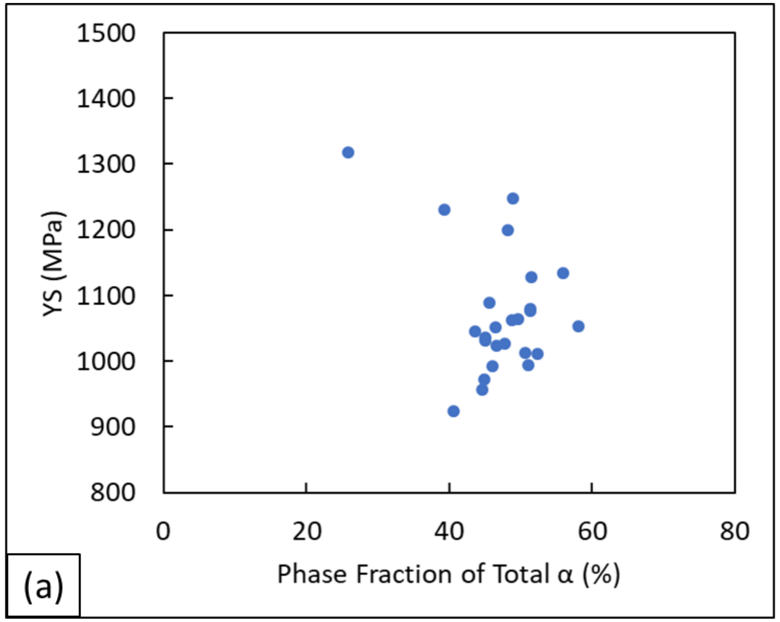
80% solid solution strengthening (“base strength”)
Average – 835 MPa

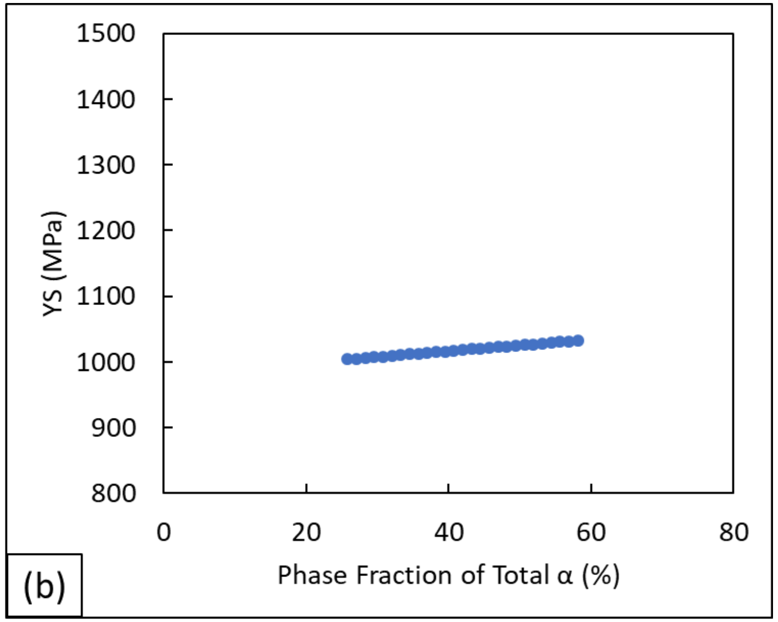
20% Hall-Petch strengthening
Average – 222 MPa

G. Lutjering, J. C. Williams, *Titanium - 2nd Edition* (Springer-Verlag, 2007).

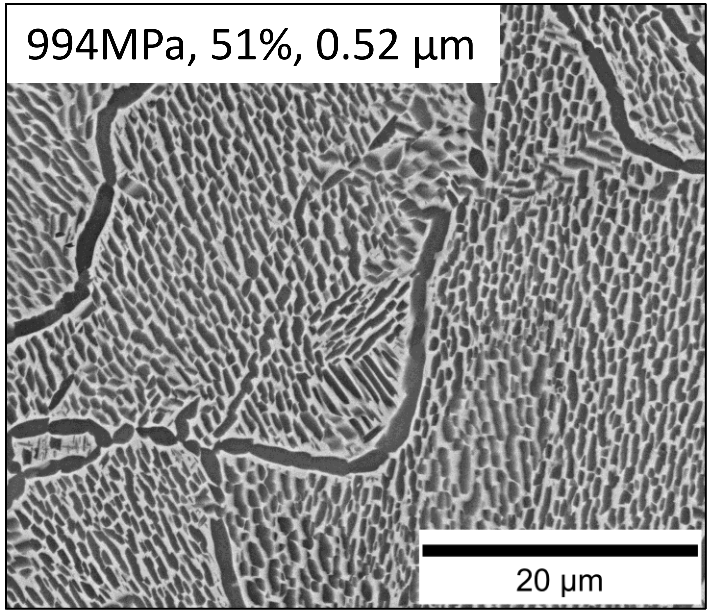


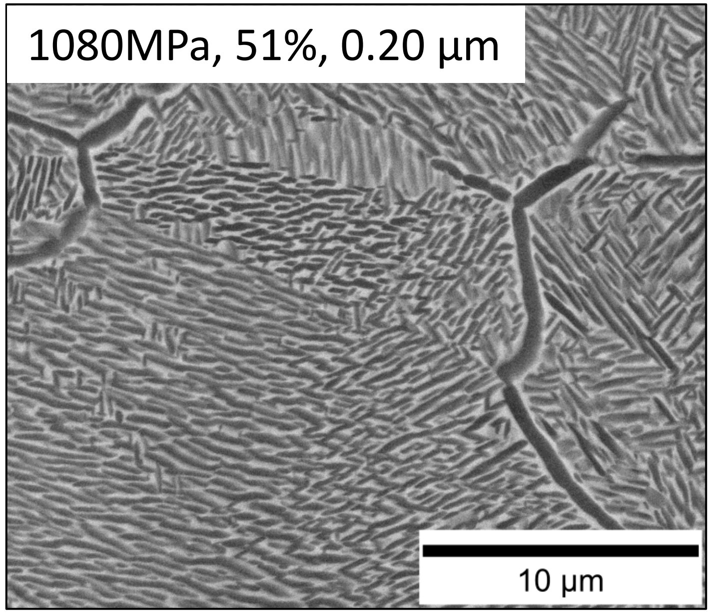


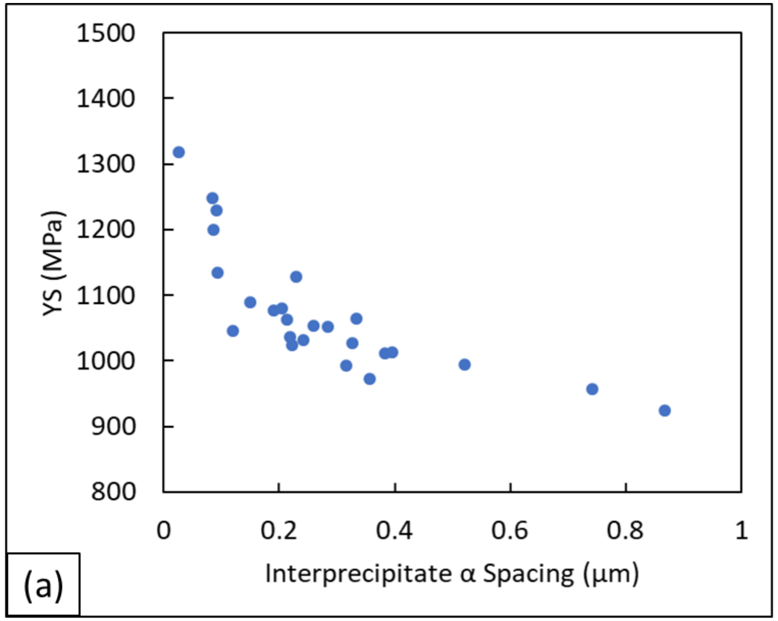


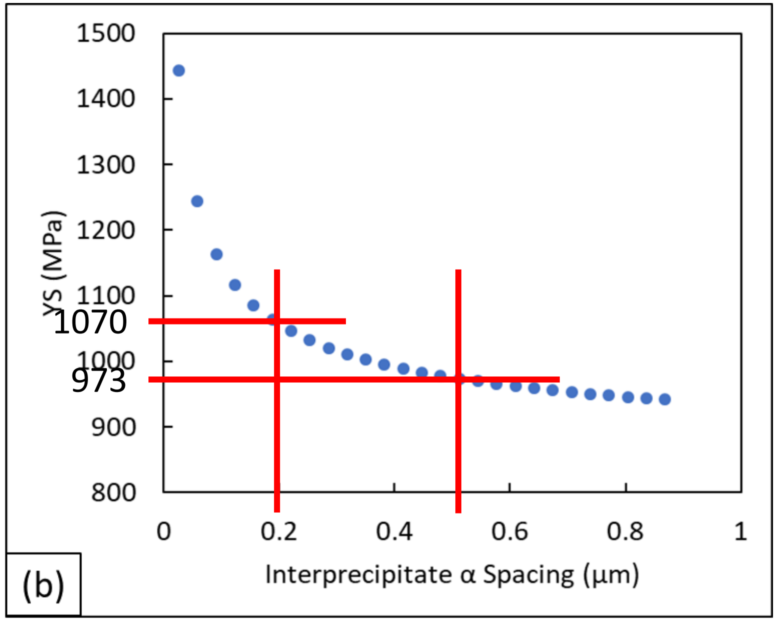


Center Proprietary – Terms of CANFSA Membership Agreement Apply


994MPa, 51%, 0.52 µm
20 µm


1080MPa, 51%, 0.20 µm
10 µm


1500
1400
1300
1200
1100
1000
900
800
YS (MPa)
0
0.2
0.4
0.6
0.8
1
Interprecipitate α Spacing (µm)
(a)


1500
1400
1300
1200
1100
1070
1000
973
900
800
YS (MPa)
0
0.2
0.4
0.6
0.8
1
Interprecipitate α Spacing (µm)
(b)

Challenges & Opportunities

- Accurate measurement of inter-lath spacings < 0.1 µm
  - STEM imaging → time/cost → $$$$
- Improve predictions of higher yield strength samples

- Prediction of optimal microstructure
- Application to other beta titanium alloys and microstructures
- Virtual yield strength measurement of synthetic microstructures
  - Time/cost savings during alloy and process development

Thank you!

Andrew Temple

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References

[1] S. D. Bartus, Evaluation of Titanium-5Al-5Mo-5V-3Cr (Ti-5553) Alloy Against Fragment and Armor-Piercing Projectiles (No. ARL-TR-4886). Army Research Laboratory, 34 (2009).

[2] Cotton, J.D., Briggs, R.D., Boyer, R.R. et al. State of the Art in Beta Titanium Alloys for Airframe Applications. JOM 67, 1281–1303 (2015). https://doi.org/10.1007/s11837-015-1442-4

[3] C. Micheletti et al., Ti-5Al-5Mo-5V-3Cr bone implants with dual-scale topography: A promising alternative to Ti-6Al-4V. Nanotechnology. 31 (2020), doi:10.1088/1361-6528/ab79ac.

[4] H. D. Carlton, K. D. Klein, J. W. Elmer, Evolution of microstructure and mechanical properties of selective laser melted Ti-5Al-5V-5Mo-3Cr after heat treatments. Science and Technology of Welding and Joining. 24, 465–473 (2019).

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