# Hybrid Structured Nickel Superalloys to Address Price Volatility and Weld/Weld Repair Based Supply Chain Issues

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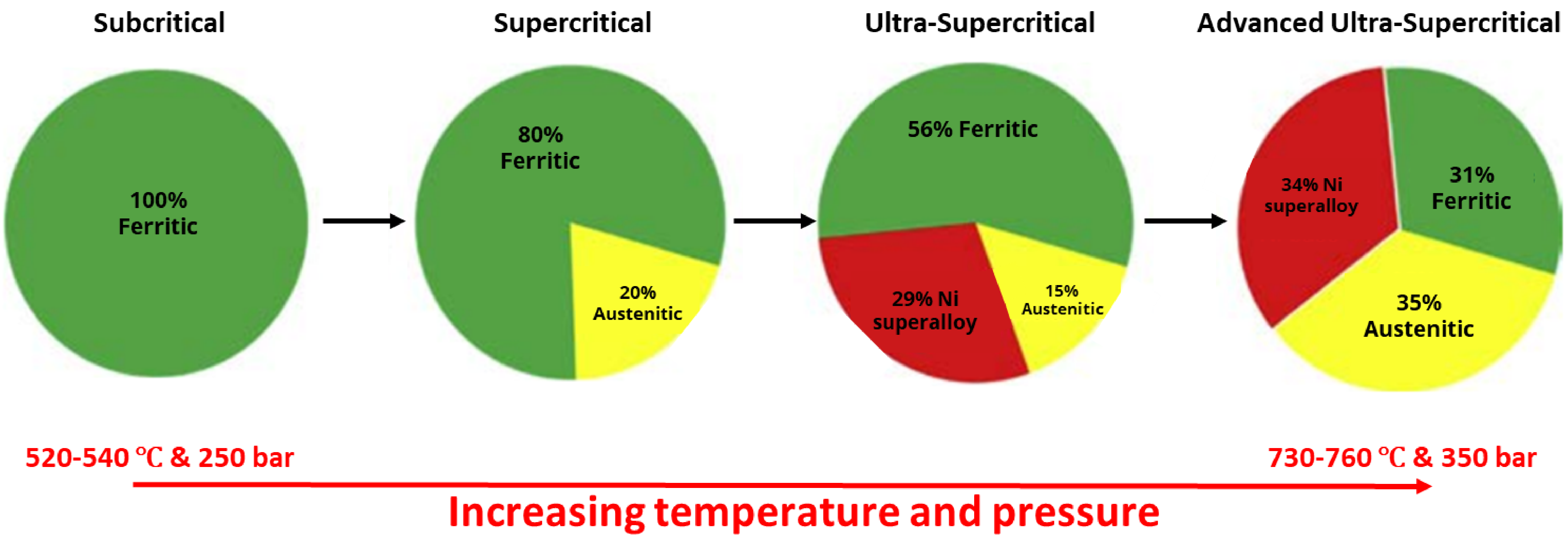
# Outline

1. Project Introduction & Goals
2. Computational Material Design
   a. CALPHAD modeling
   b. Property modelling
3. Experimental Material Design
   a. Sample creation, forging, processing
   b. Microstructure characterization
   c. Property characterization
   d. Cracking performance
4. Next Steps & Summary

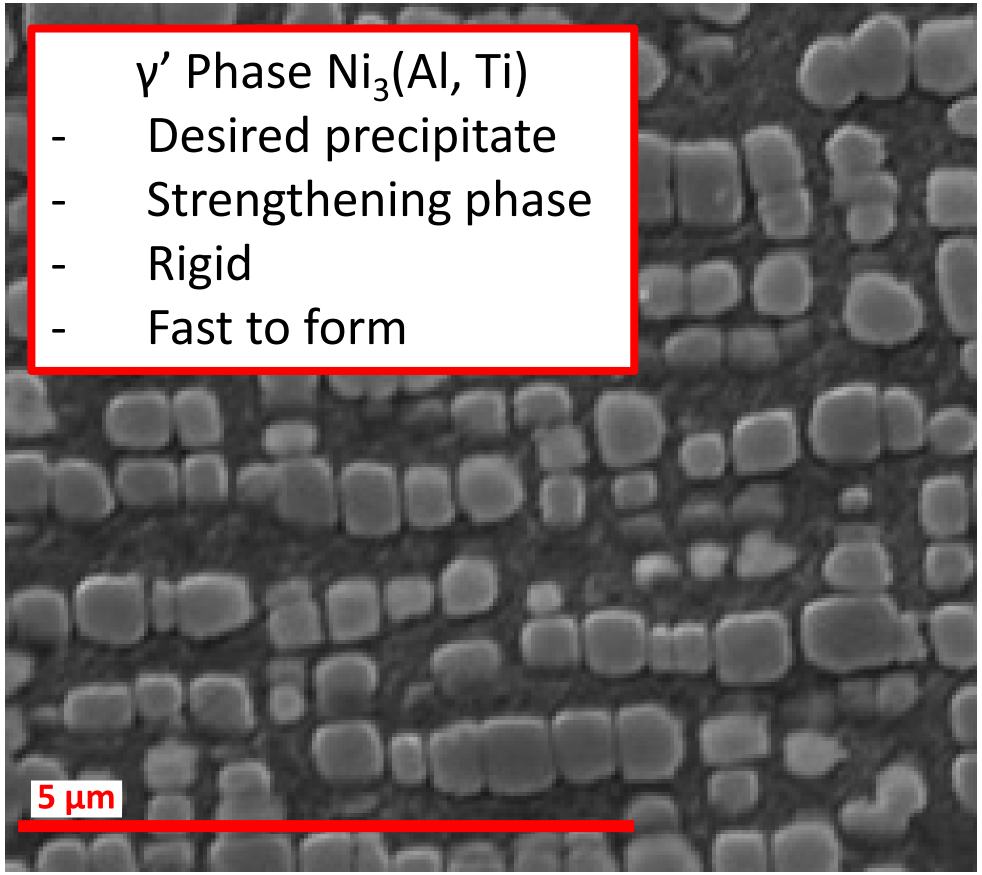
# Desire to push to higher temperatures and pressures for efficiency; demands new materials

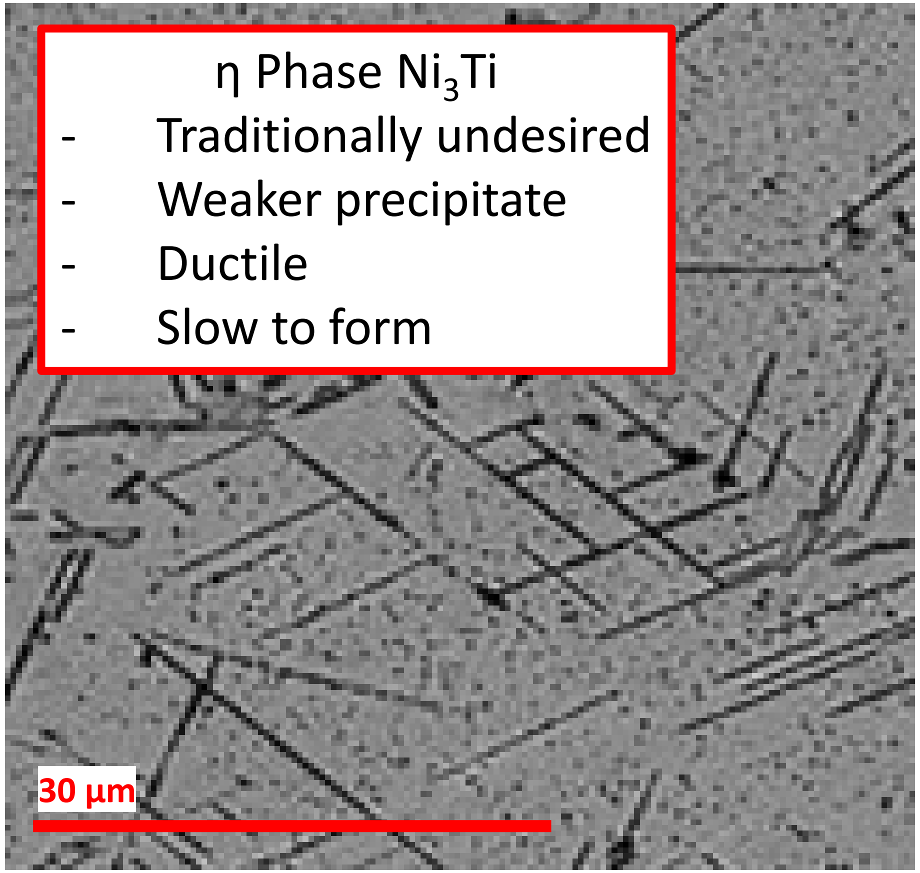


# Design a nickel superalloy that:

- Reduces cobalt content to less than 5wt% and minimize overall cost
    1. Alloy cost
- Meets weldability indices as measured by cracking resistance
    2. Solidification cracking resistance
    3. Strain age cracking resistance
- Maintains nano-indentation & hot-hardness values within 10% of a comparable superalloy (Nimonic 263)
    4. Material strength
    5. Creep resistance

# Potential to use both γ’ and η precipitates for weldability and material properties

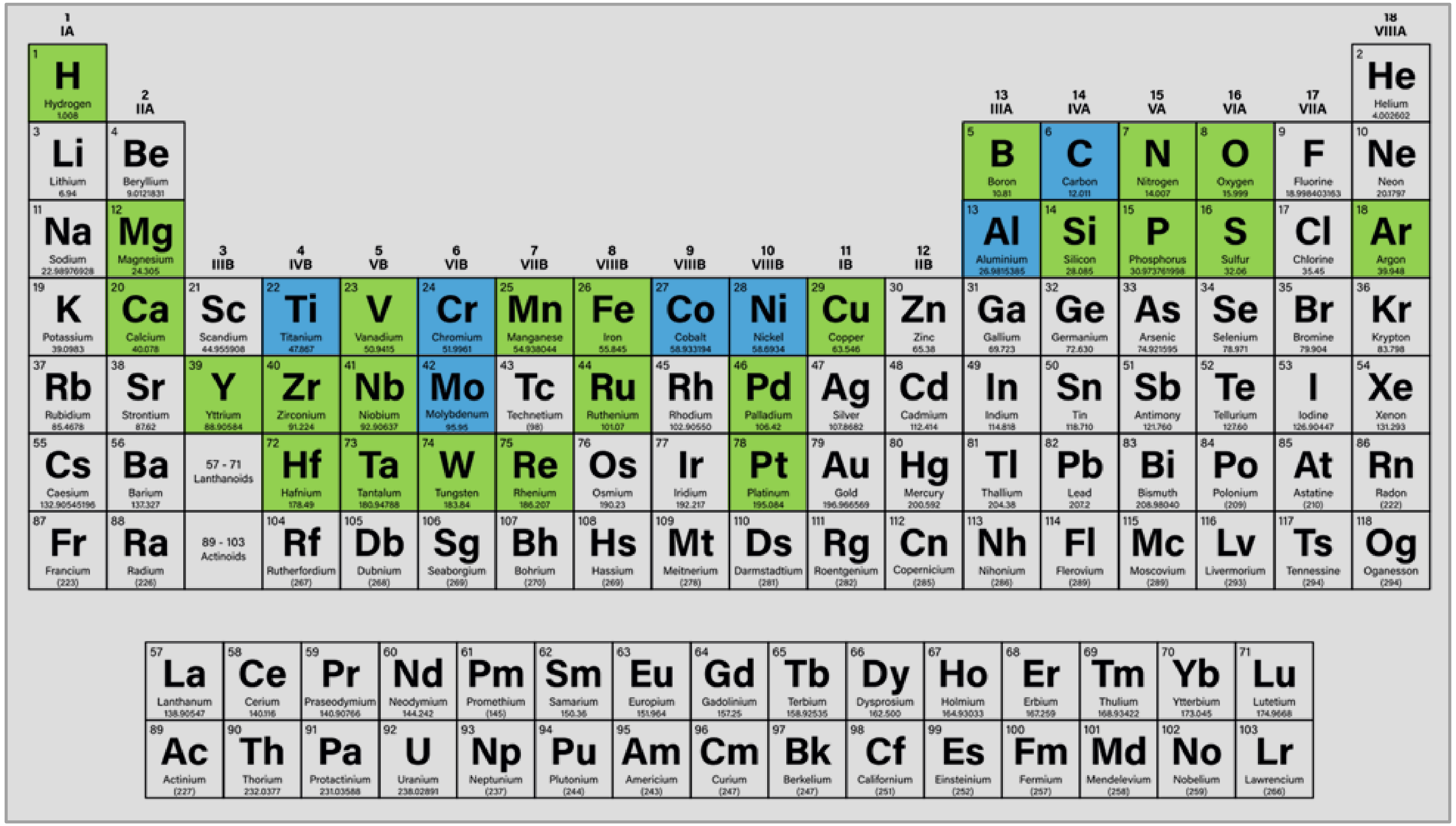



Michigan Technological University


**“Gamma prime,”** ***Gamma Prime - an overview | ScienceDirect Topics.***
**Wong, Sanders, Shingledecker, White** – Design of an ETA-phase-precipitation-hardenable nickel-based alloy …

# Design space explored previously within TCNI12 CALPHAD database




Major constituents (>15wt%):

- Ni, Cr

Minor constituents (<15wt%):

- Co, Mo

Precipitate formers (<3wt%):

- Al, Ti

Other elements tested and not selected:

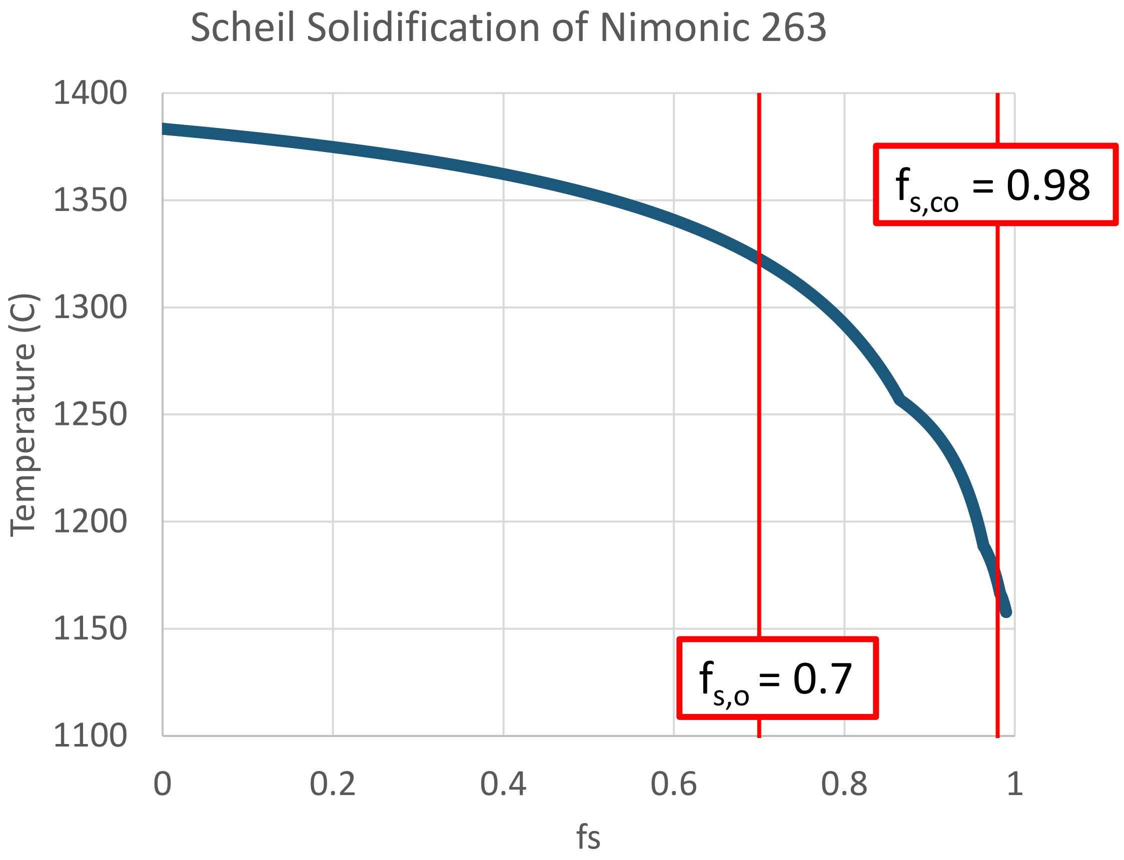
- V, Fe, Nb, W

# Solidification cracking resistance assessed via CALPHAD Scheil calculation

- Last year demonstrated limitations with automation in Kou cracking model
- Favored Easton hot tearing model
- Both are now featured & automated within ThermoCalc package!

$$Score_{Kou.Solid} = max\left(\left|dT/d(f_s)^{1/2}\right|\right)$$

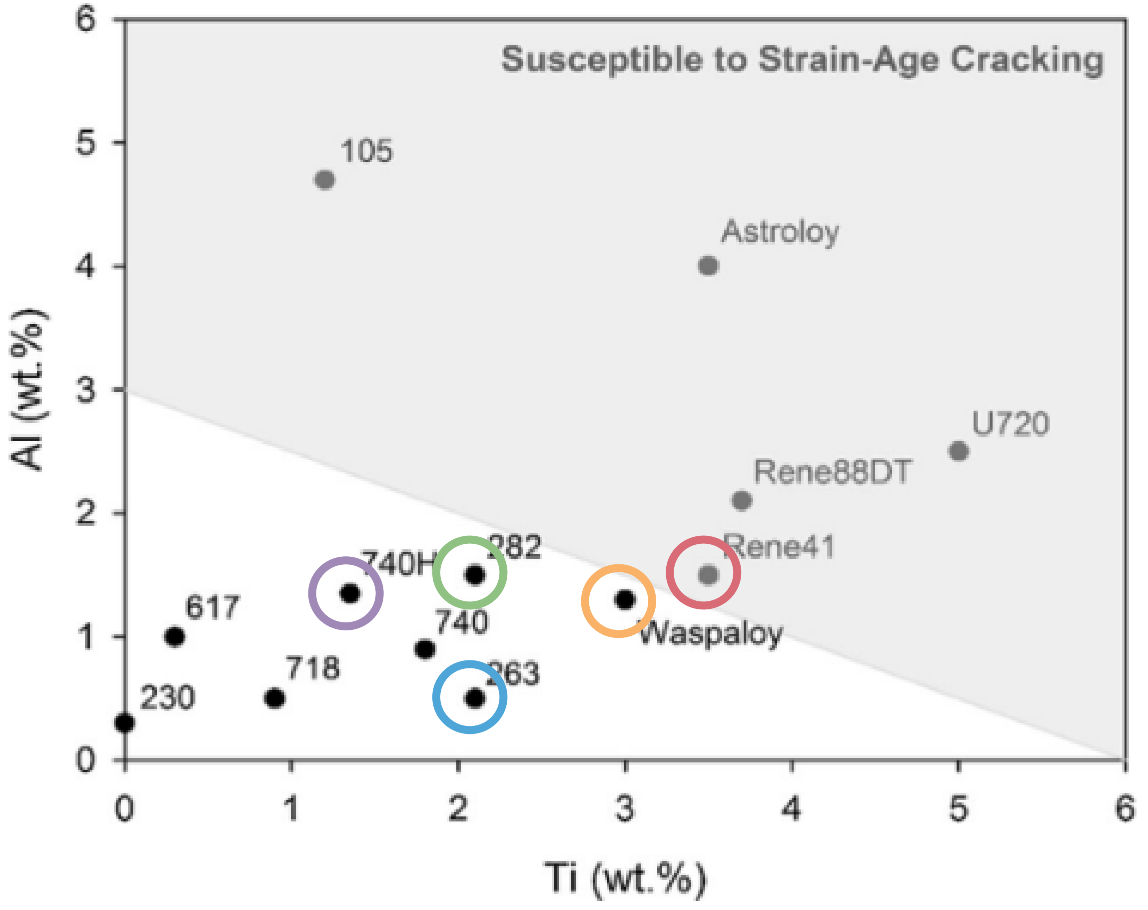
$$Score_{Easton.Solid} = \int_{To}^{Tco} f_s(T)dT$$

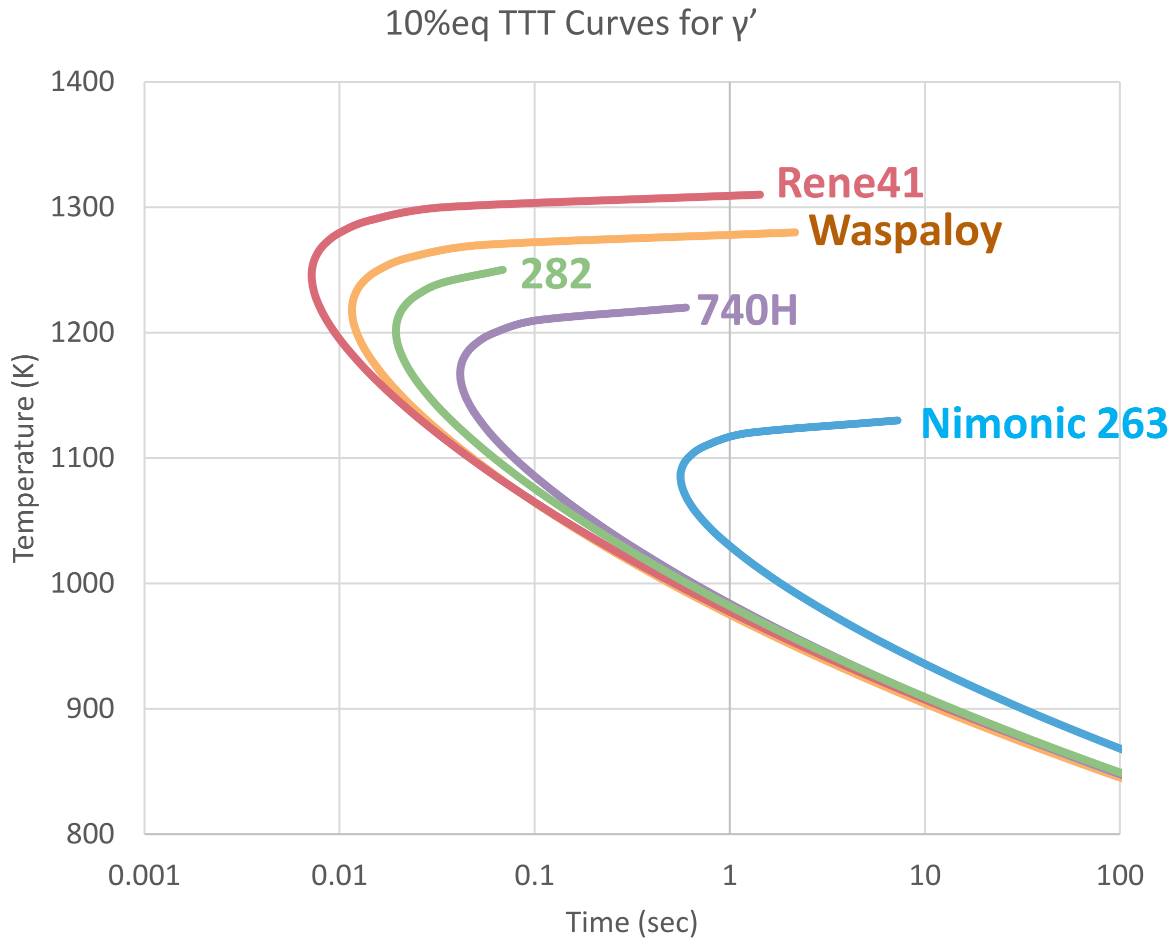





**Benoit, Zhu, Abbott, Easton** – Evaluation of the effect of RE additions on the hot tearing susceptibility of Al7150 …
**Easton, Gibson, Zhu, Abbott** – An a priori hot-tearing indicator applied to die-cast magnesium-rare earth alloys
**Liu, Kou** – Susceptibility of ternary aluminum alloys to cracking during solidification

# Strain-age cracking resistance correlated with slower γ' kinetics

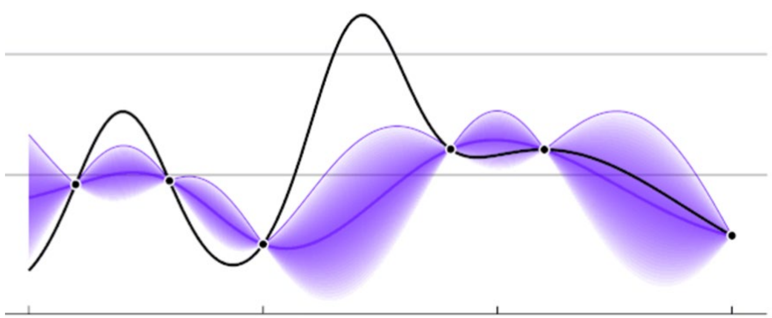


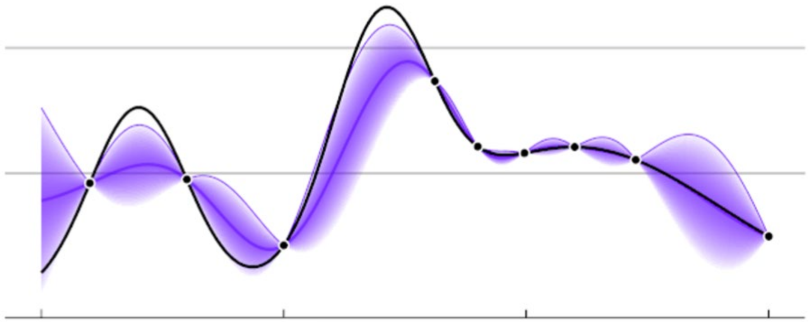



**Hardy, Detrois, et al** – Solving Recent Challenges fro Wrought Ni-Base Superalloys **Sims, Hagel** – The Superalloys
**Tang, Reed, et al** – Alloys-By-Design: Application to new superalloys for additive manufacturing

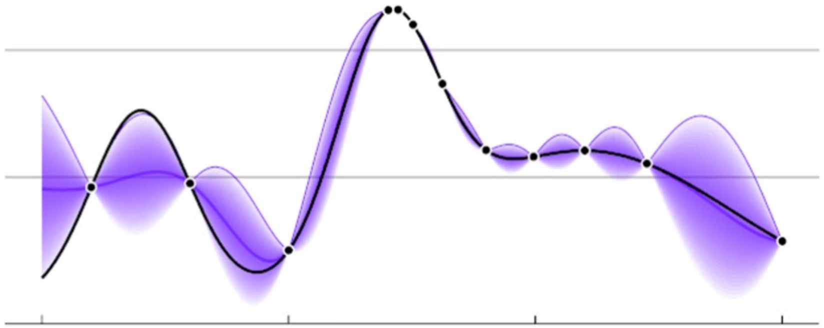
# Utilize Bayesian Optimization to efficiently optimize simulated material properties



Initial BO does not find maxima



More calculations reduce uncertainty



Efficiently locate maxima

Explore high variance regions
Exploit high reward regions



Images used from gif at: https://en.wikipedia.org/wiki/Bayesian_optimization

# Best optimized alloys for small-scale testing

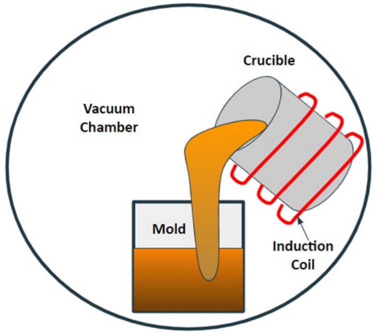
| Rank | Co | Cr | Mo | Al | Ti | C | Ni |
|---|---|---|---|---|---|---|---|
| Opt1 | 5.0 | 18.6 | 9.9 | 0.53 | 2.37 | 0.06 | 63.53 |
| Opt2 | 5.0 | 18.5 | 5.17 | 0.64 | 2.91 | 0.07 | 67.71 |
| Opt3 | 9.5 | 18.5 | 5.07 | 0.73 | 3.77 | 0.07 | 62.34 |
| Nimonic 263 | 20.5 | 19.9 | 5.7 | 0.27 | 2.1 | 0.07 | 51.46 |

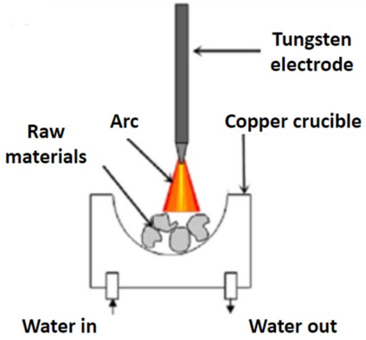
All in wt%

Compositions shown generated with Superalloy MOBO script version 6 (Sv6)

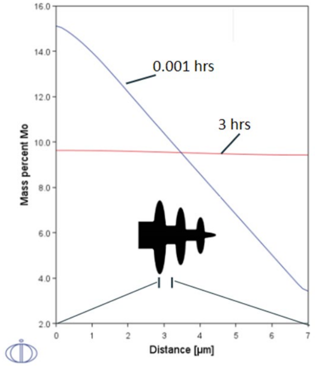
# Sample Creation/Processing Map

### Vacuum Induction Melting (VIM) or Arc Melting



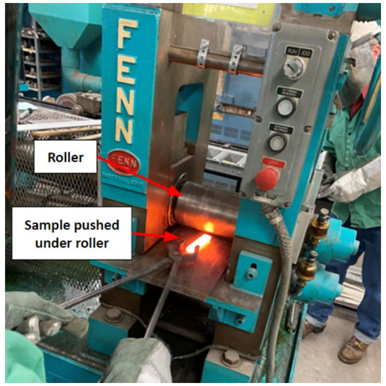




### Homogenization

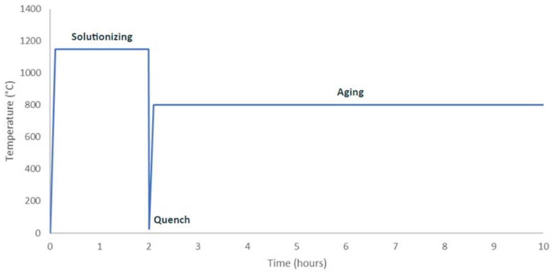



### Forging


### Hot Rolling

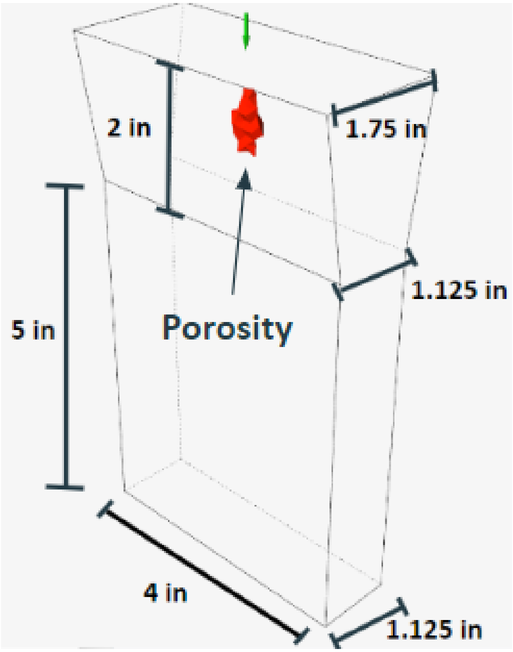



### Heat Treating

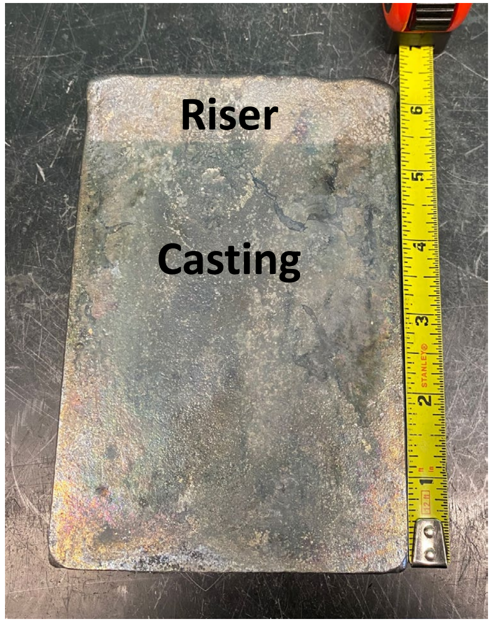


# Small-scale samples cast via VIM and Arc Melting for comparison

Inspire Cast Simulation




Side View of Casting



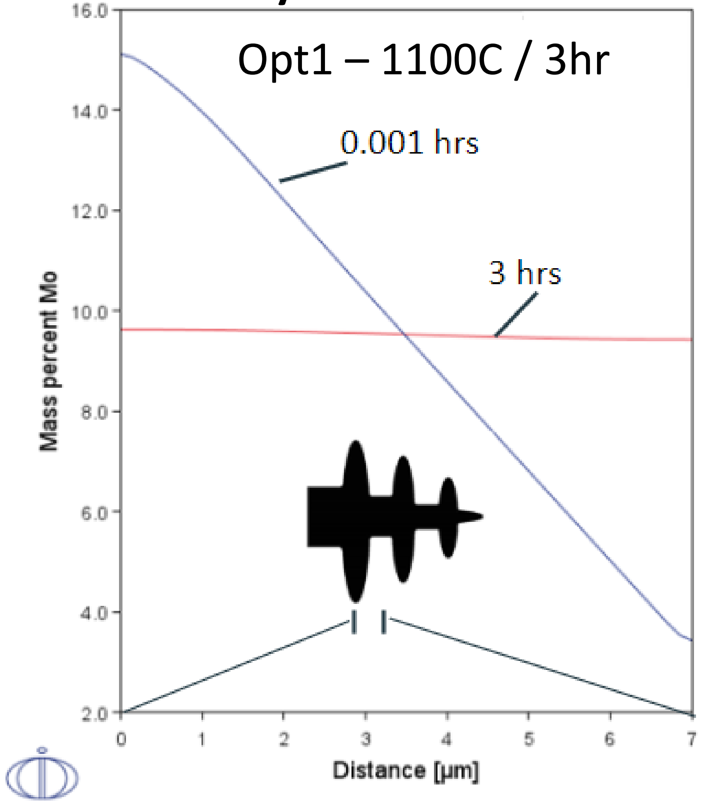

**VIM melts only for Opt1**

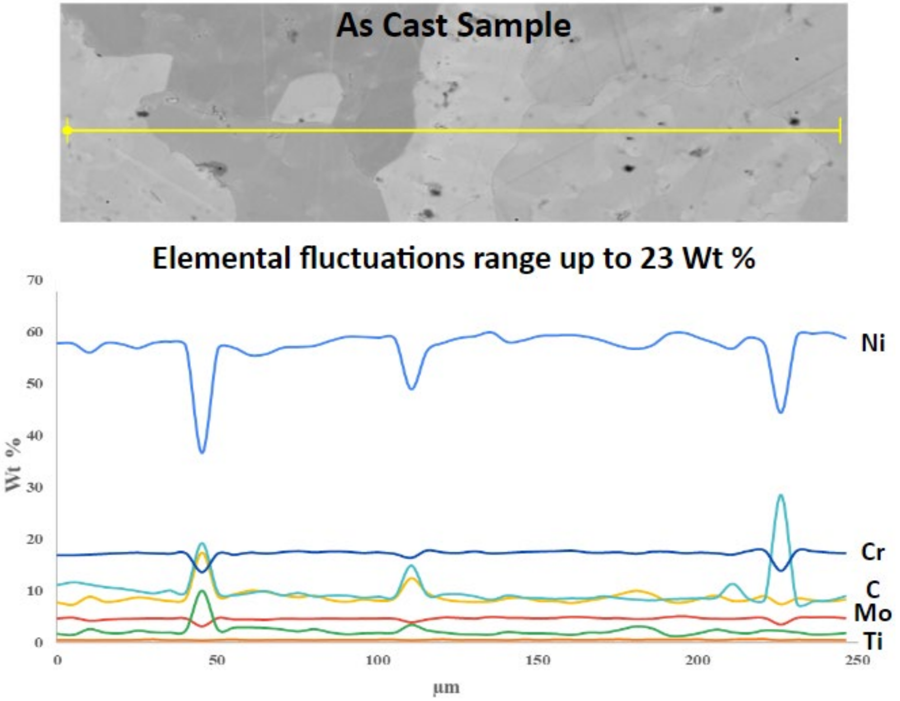


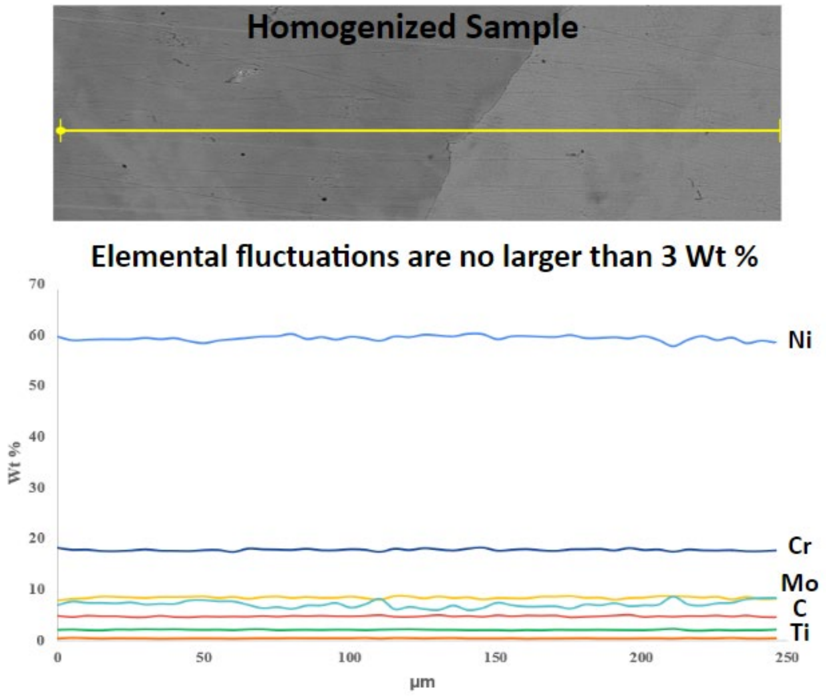
**Arc Melts for Opt1, 2, 3**

# Homogenization performed with N263 process successfully

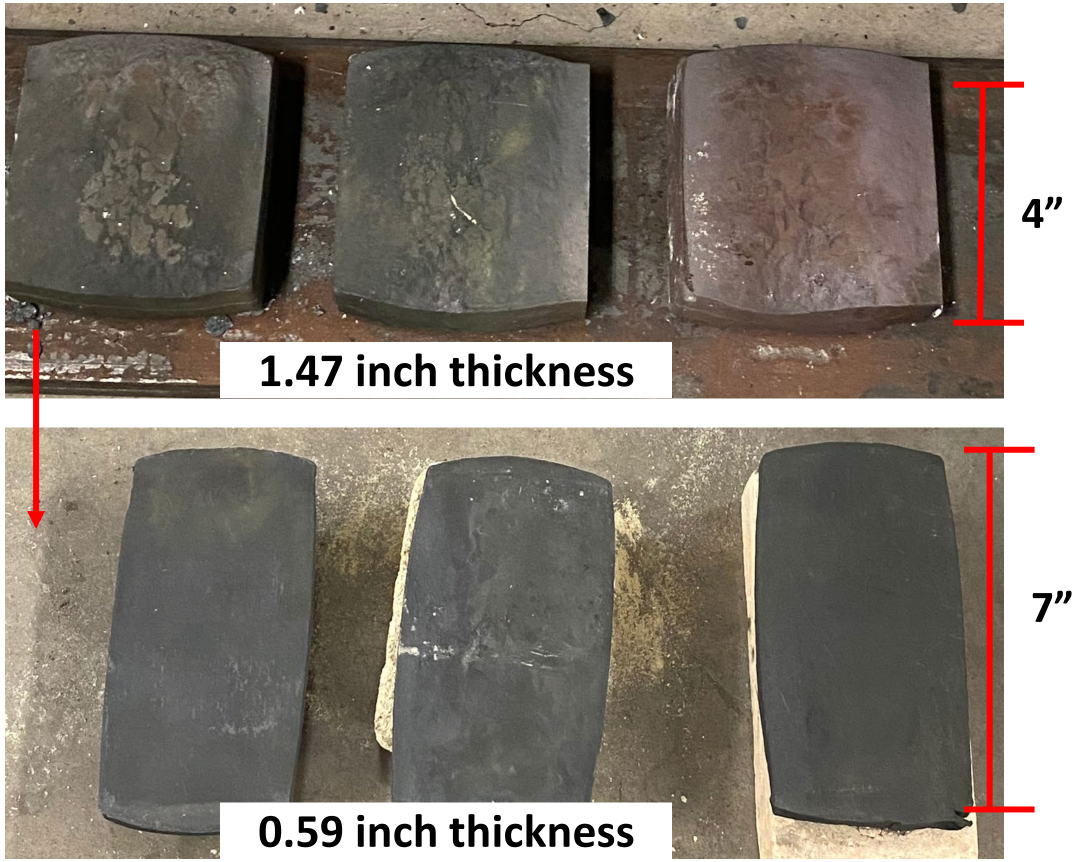
**Diffusivity confirmed via Dictra**



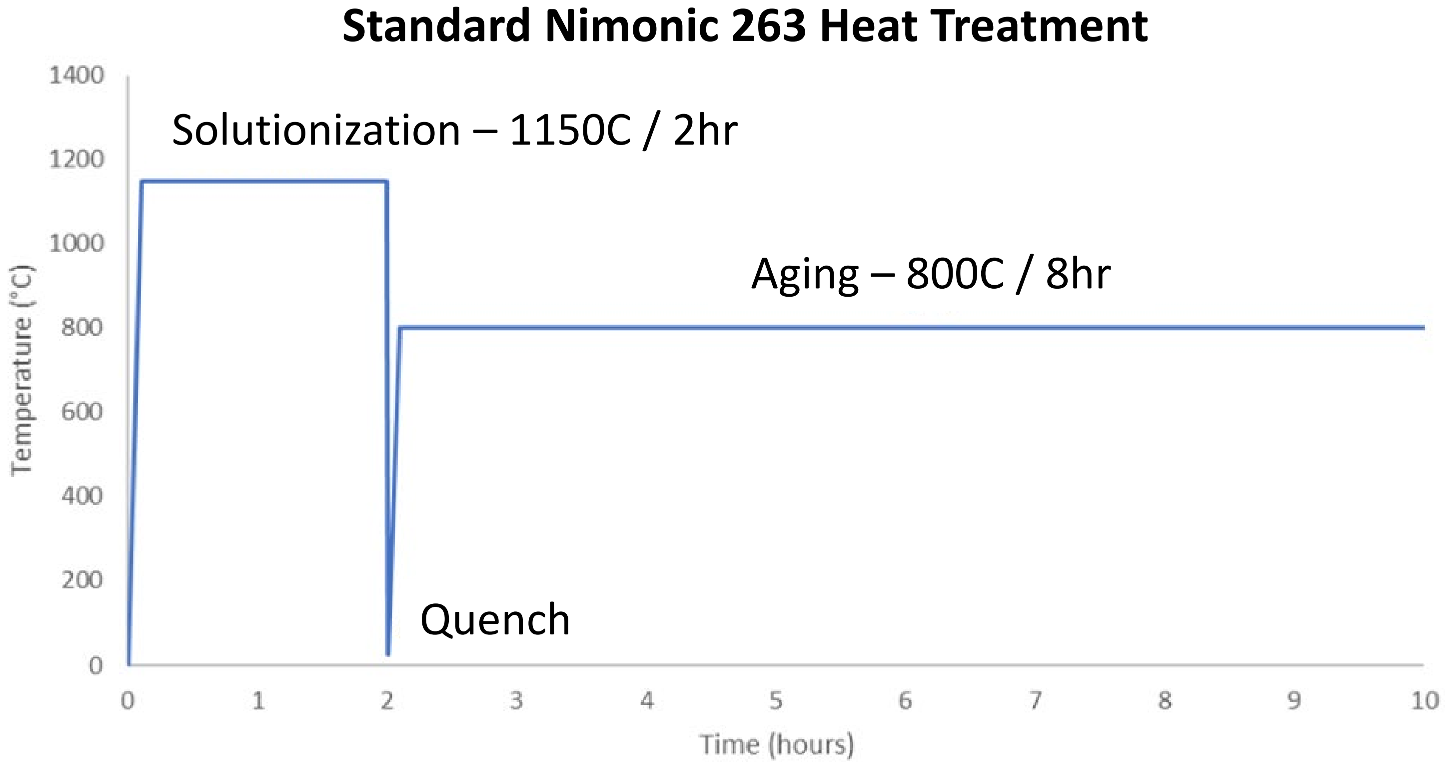



# In-house forging and hot rolling on all VIM/Arc samples

# Heat treatment varied to explore standard and over-aged conditions

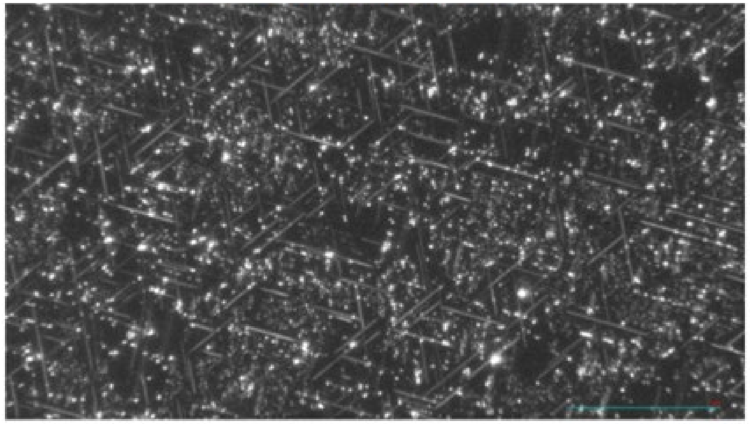



**Aging Treatment**

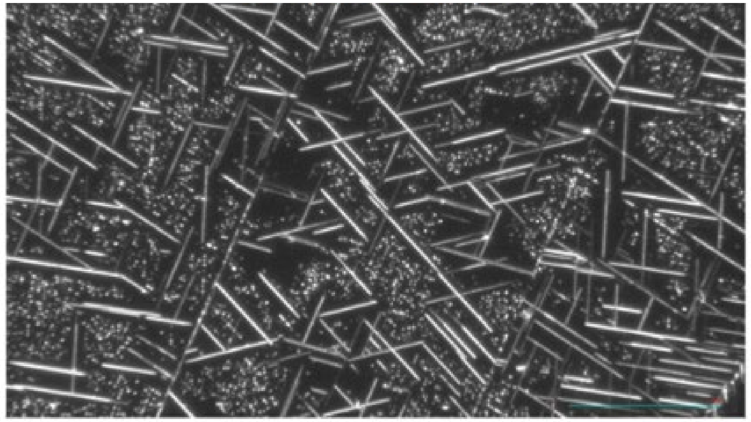
| Sample | Casting | Time (h) | Temp (C) |
|---|---|---|---|
| Opt1 | VIM | 8 | 800 |
| Opt1 | VIM | 1000 | 800 |
| Opt1 | VIM | 1000 | 850 |
| N263 | Commercial | 8 | 800 |
| N263 | Commercial | 1000 | 800 |
| N263 | Commercial | 1000 | 850 |
| Opt1 | Arc | 8 | 800 |
| Opt2 | Arc | 8 | 800 |
| Opt3 | Arc | 8 | 800 |

# Optical microscopy and point counting used for volume fraction analysis

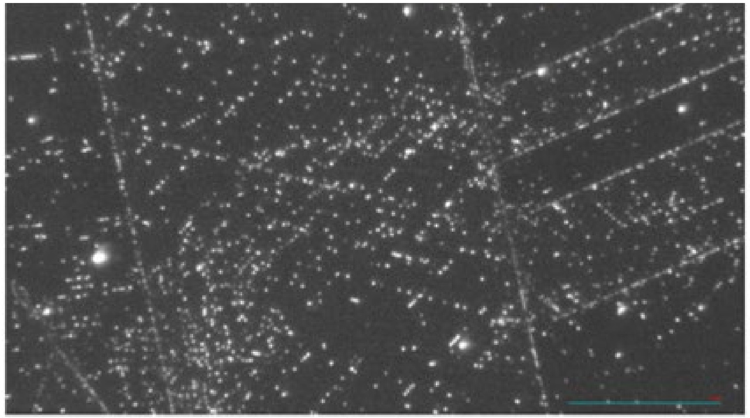
Opt1 – 800C / 1000hr



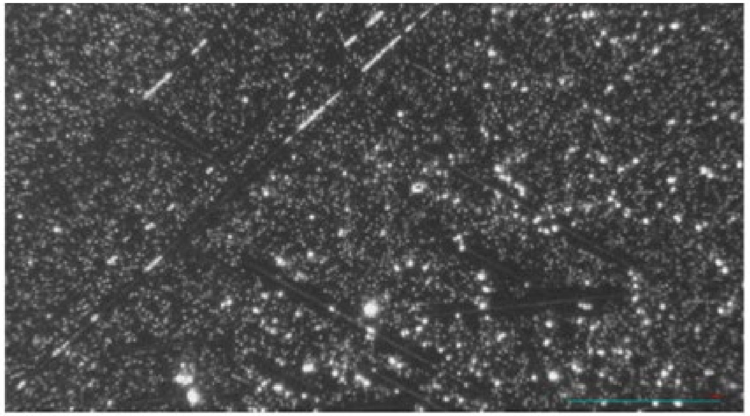
Opt1 – 850C / 1000hr



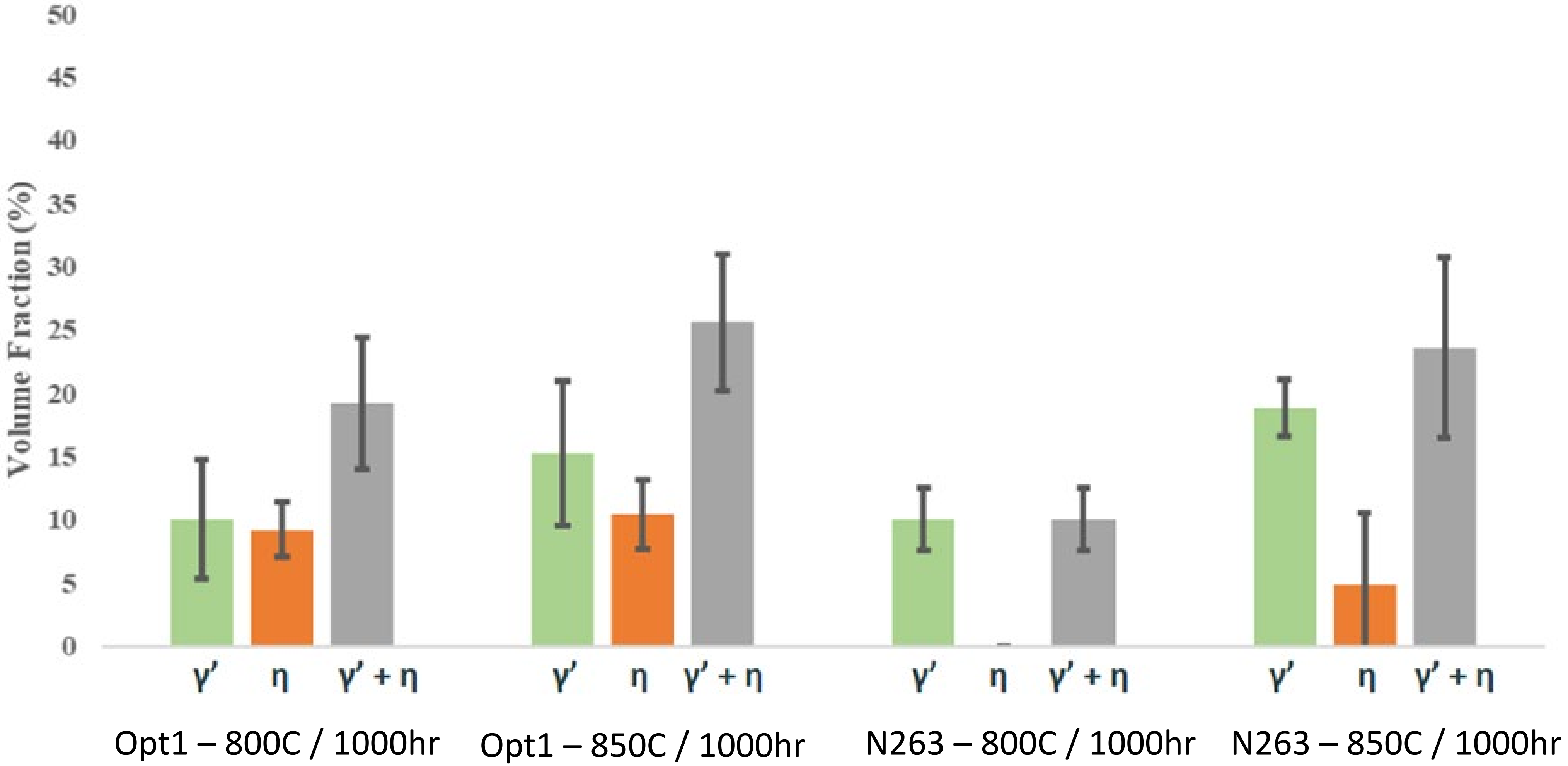
N263 – 800C / 1000hr



N263 – 850C / 1000hr

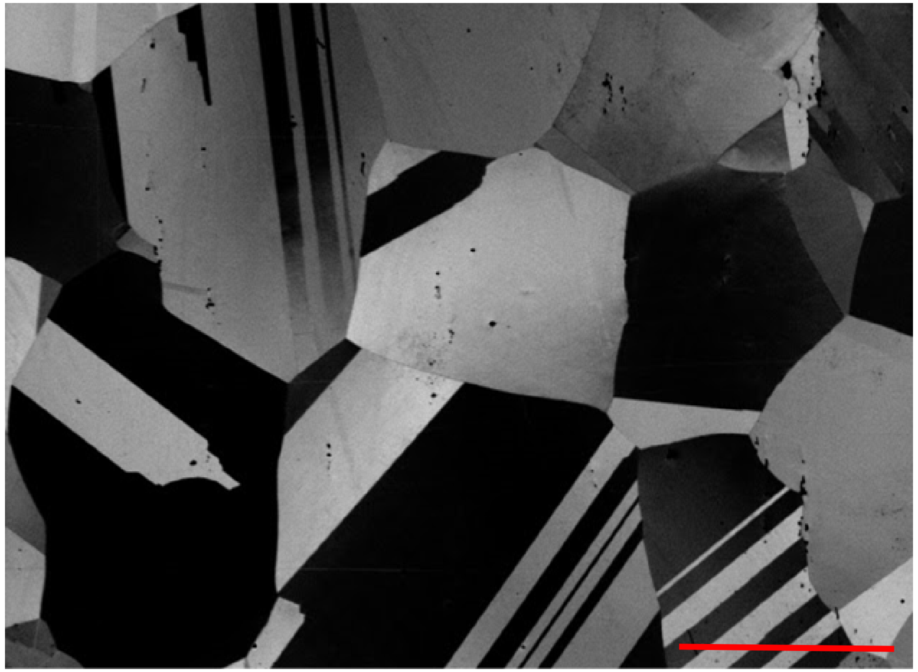


# Optimized samples have higher η volume fractions and comparable γ’

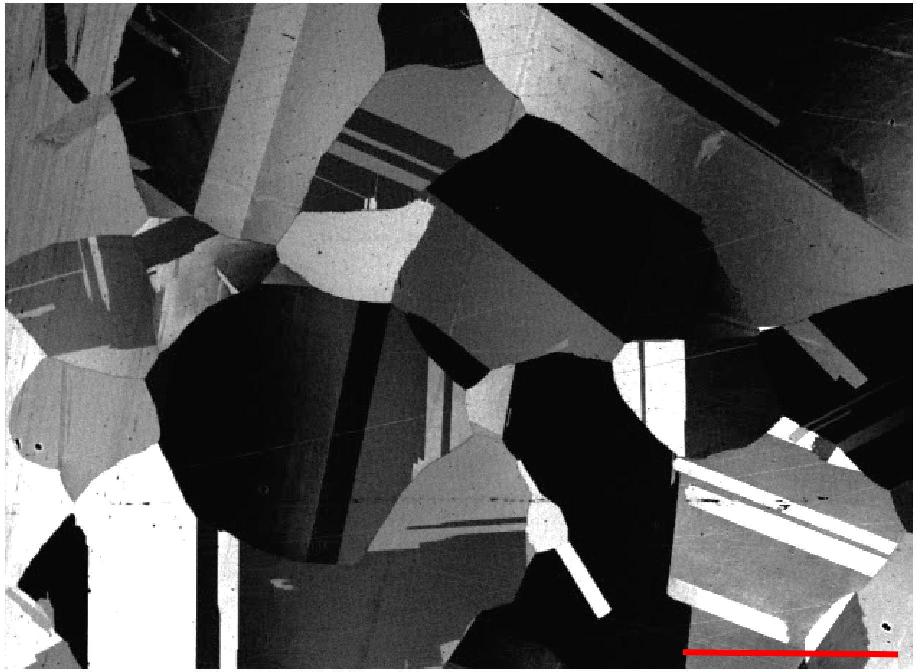


# Grain sizes between samples are comparable across tested heat treatments

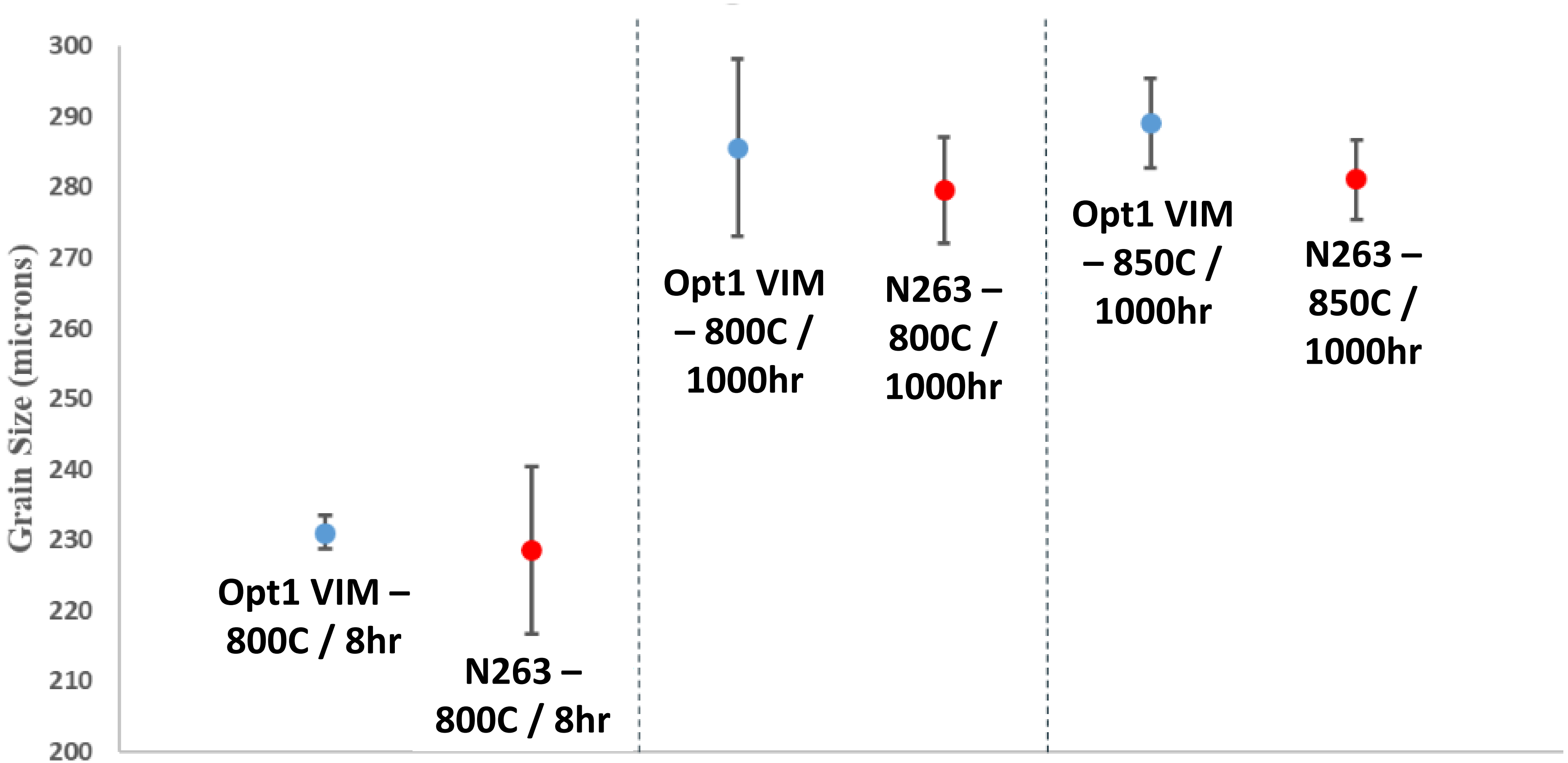
**N263 – 800C / 8hr d = 230 ± 10 µm**



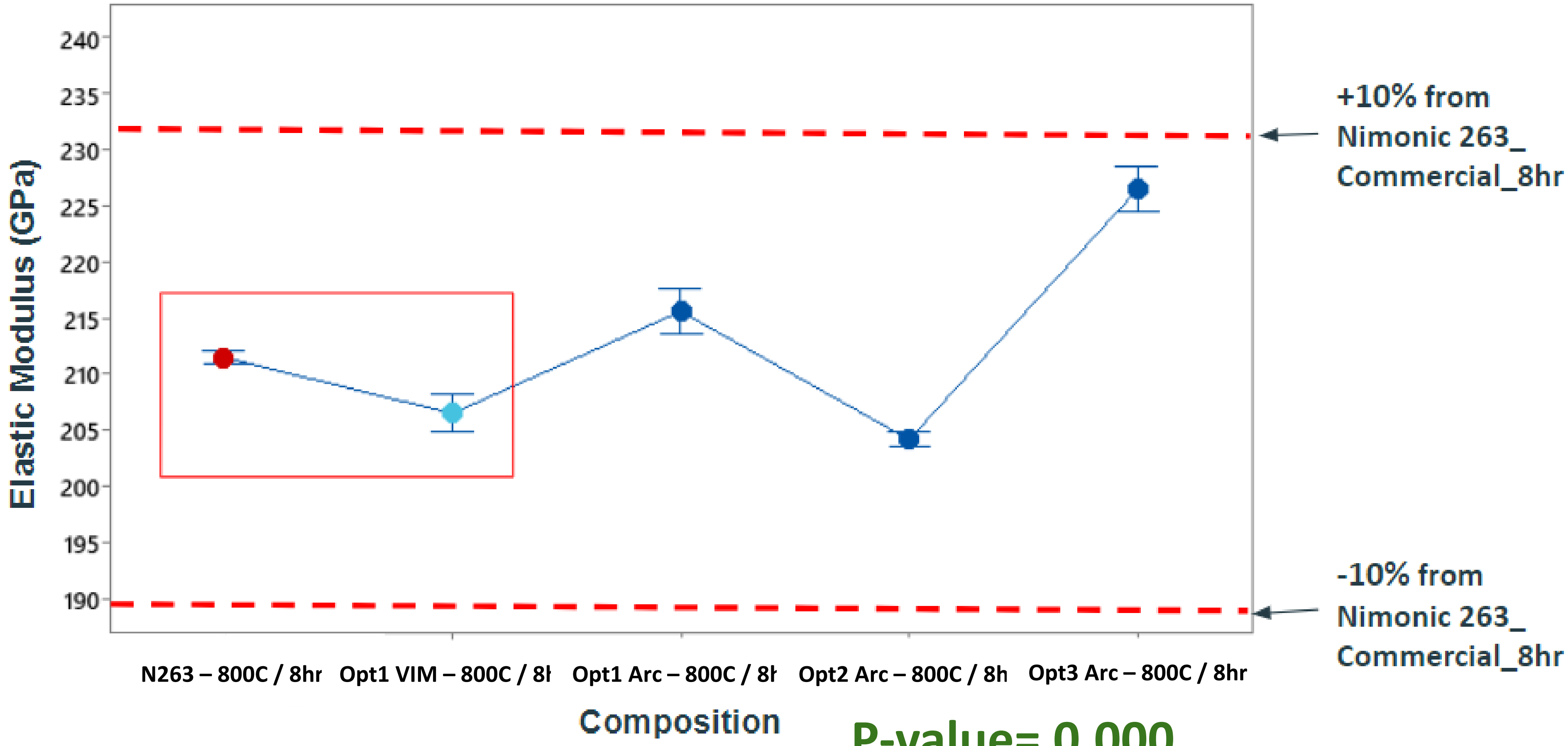

**Opt1 VIM – 800C / 8hr d= 231 ± 2 µm**



# Grain sizes between samples are comparable across tested heat treatments

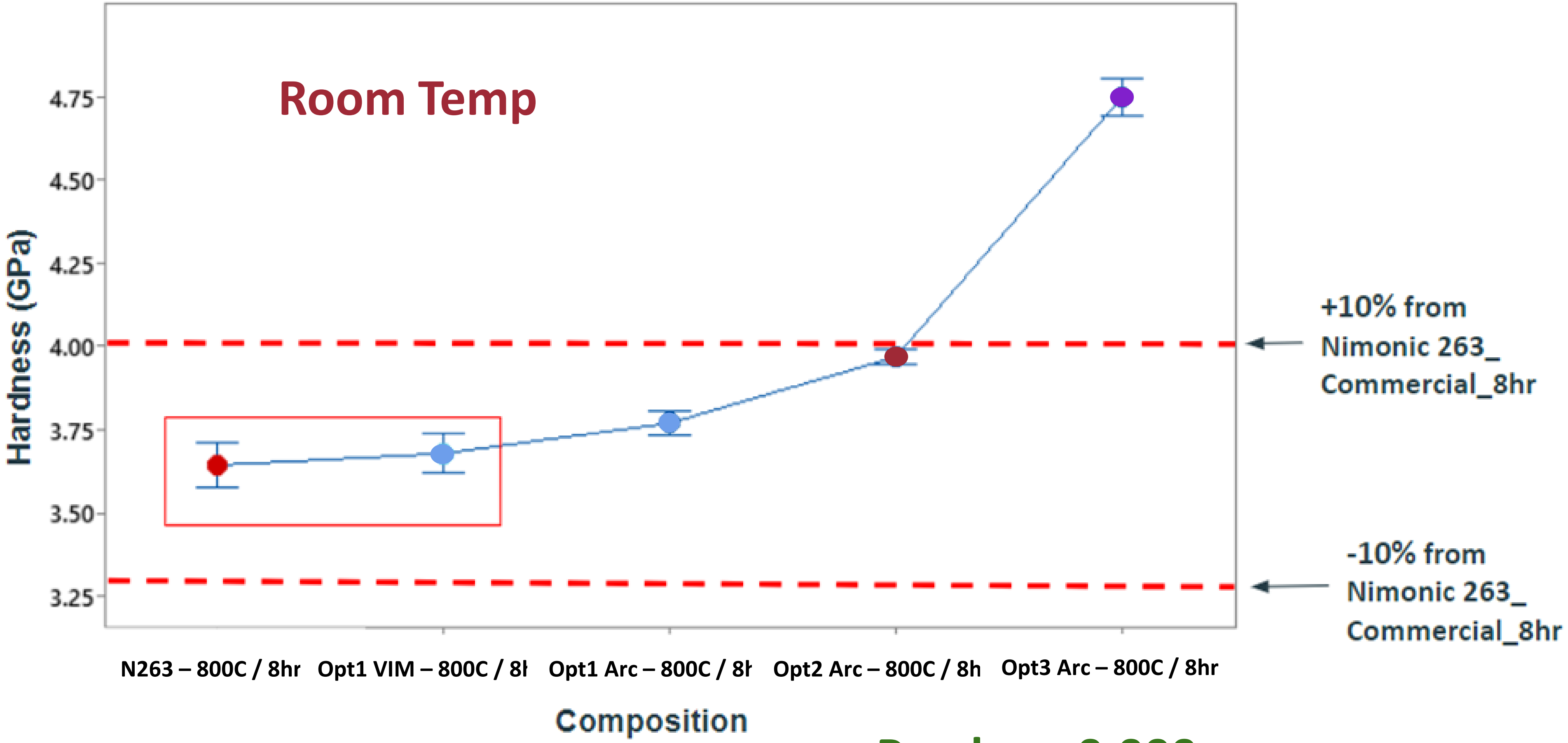


# Elastic moduli show variance but are all within desired range



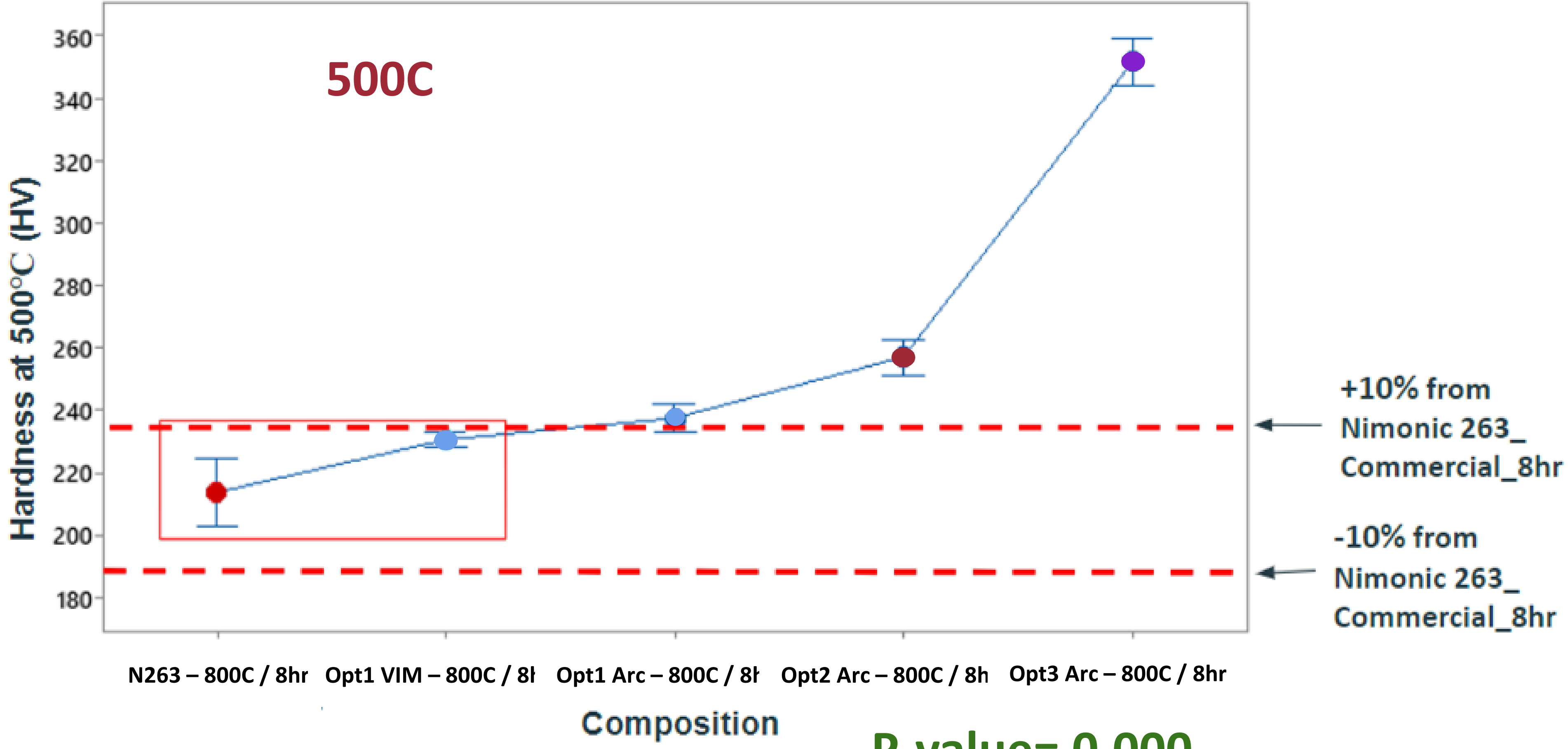

**P-value= 0.000**

# Opt3 composition exhibits with significant RT hardness that other samples



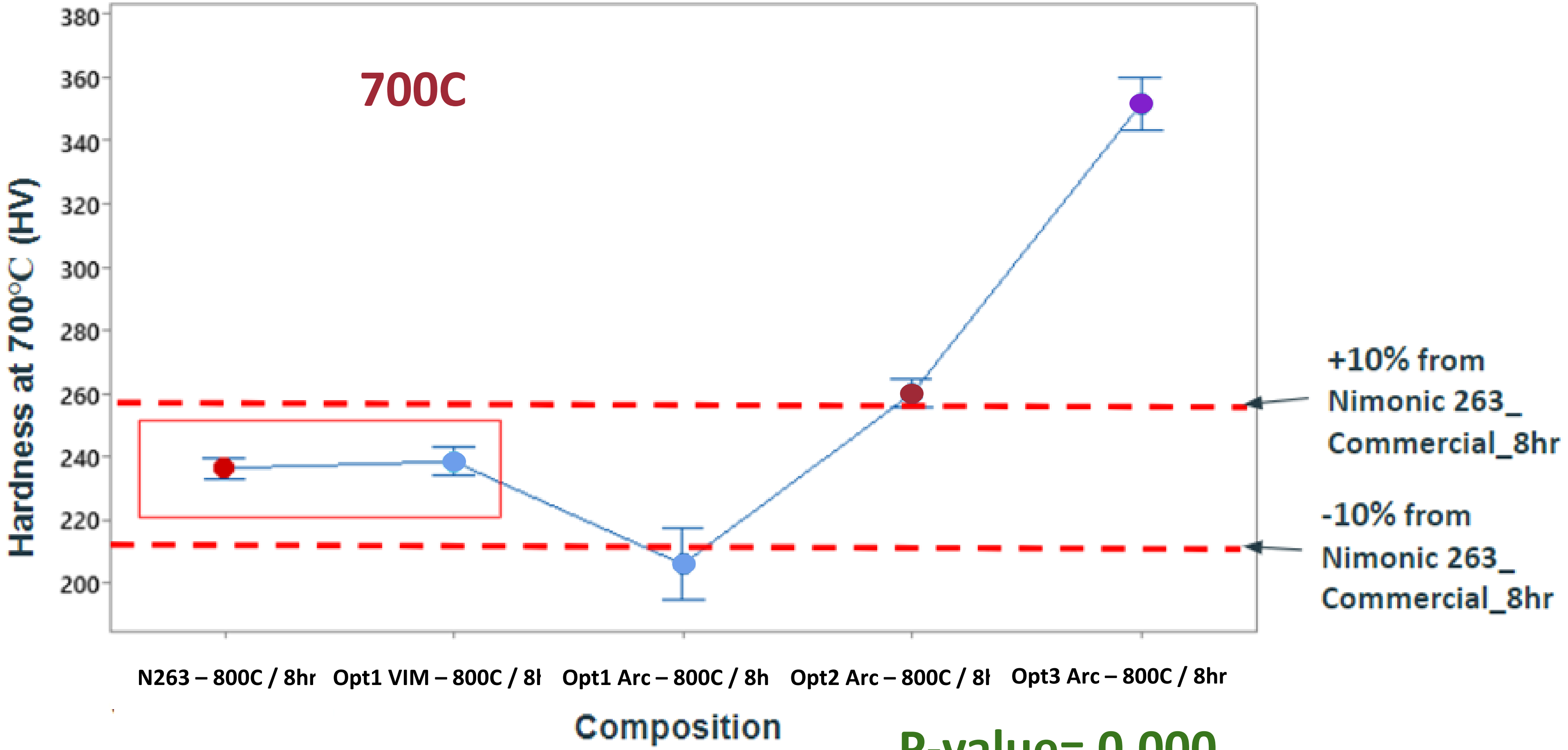

**P-value= 0.000**

# As temperature increases, optimized alloys perform better than N263



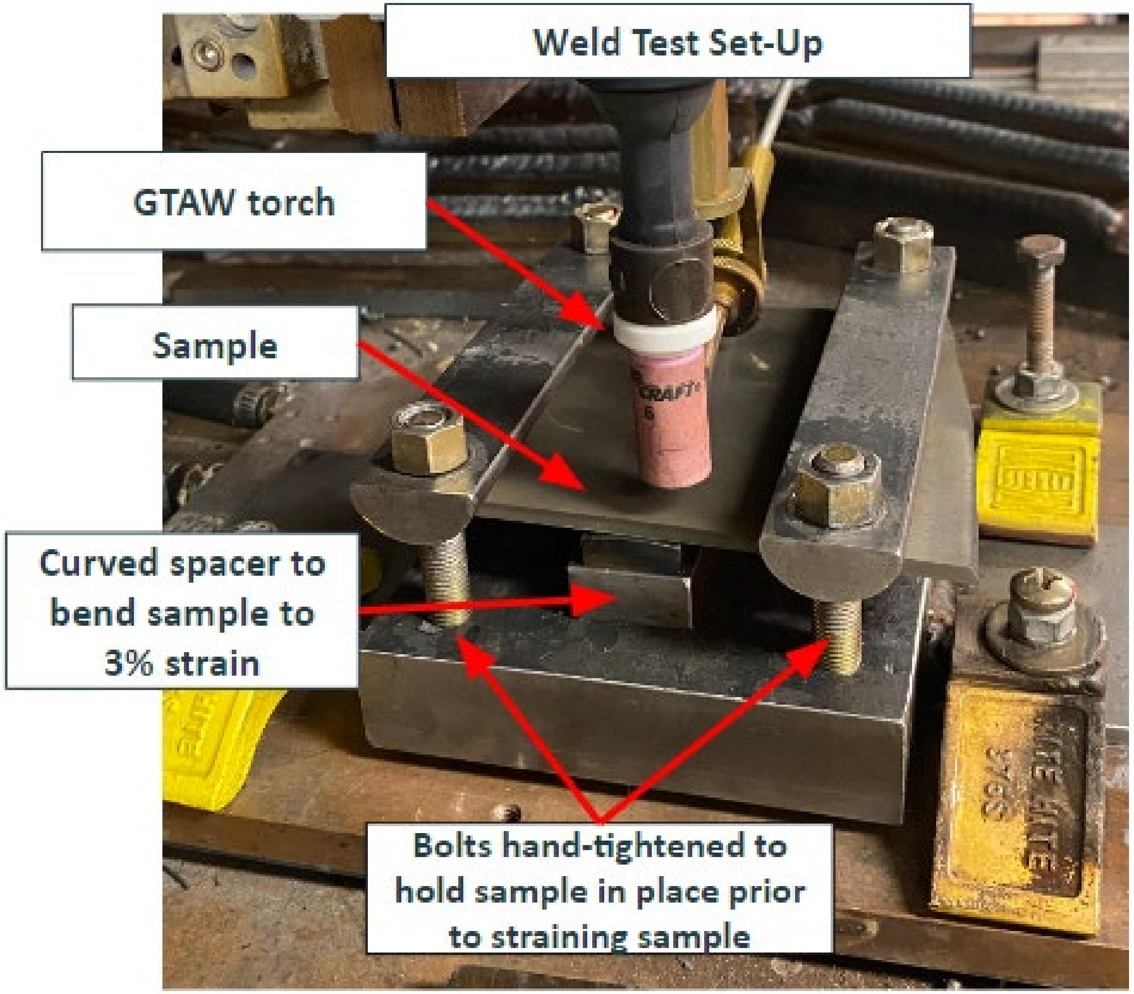

P-value= 0.000

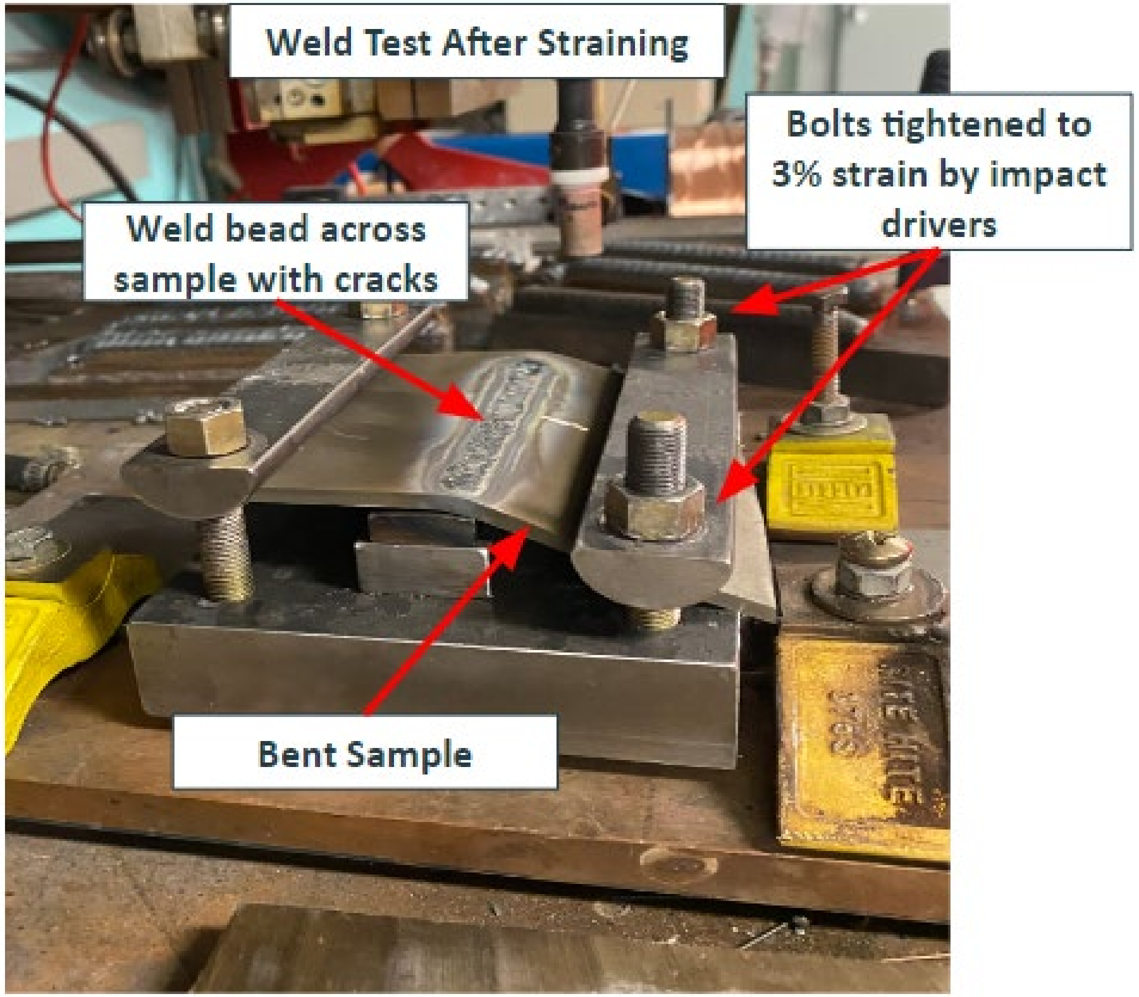
# At operation temperature, Opt1 compositions both fall in hardness, Opt2/3 continue to outperform




P-value= 0.000

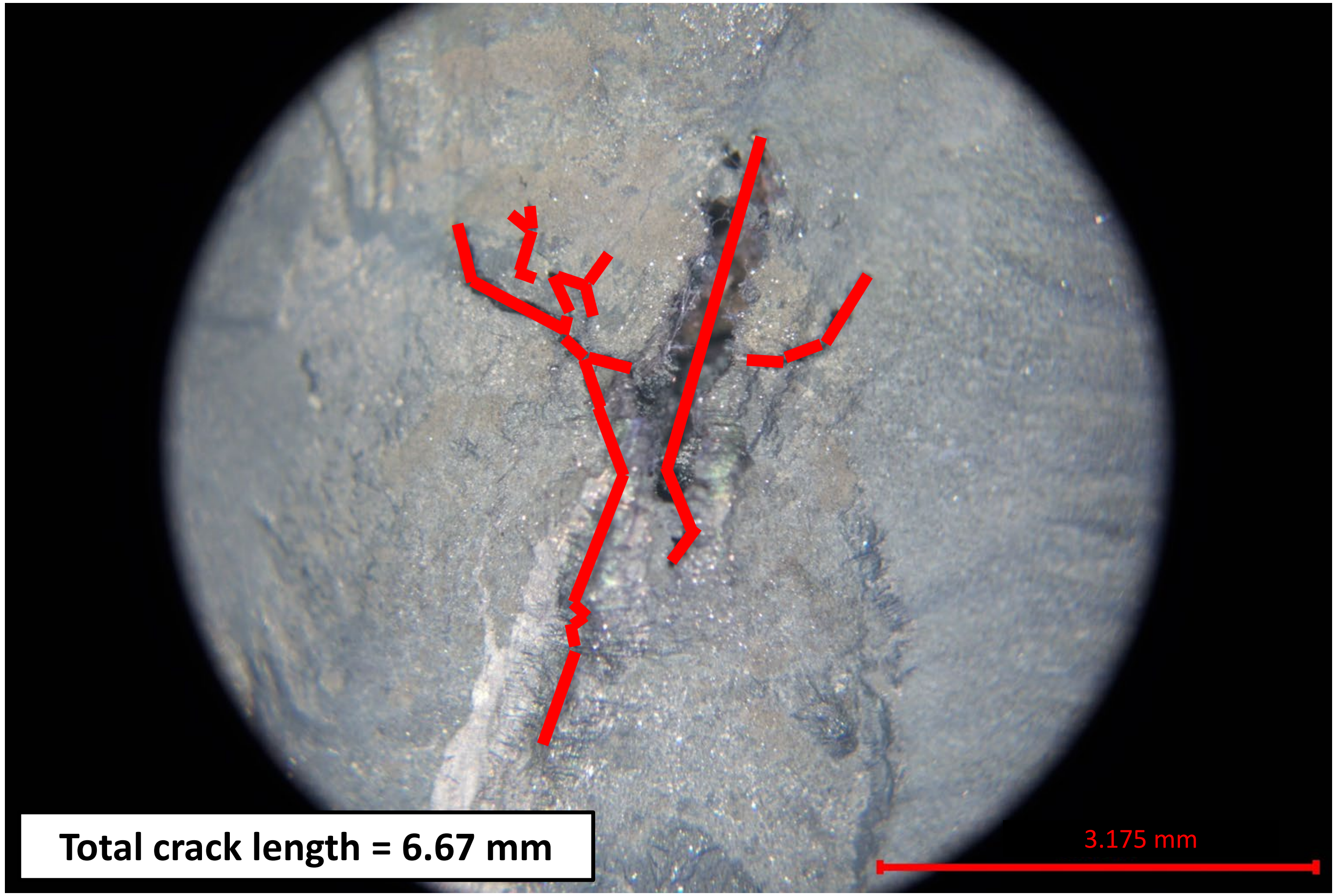
# Trans-Varestraint weldability test rig created in-house at Michigan Tech to test solidification cracking



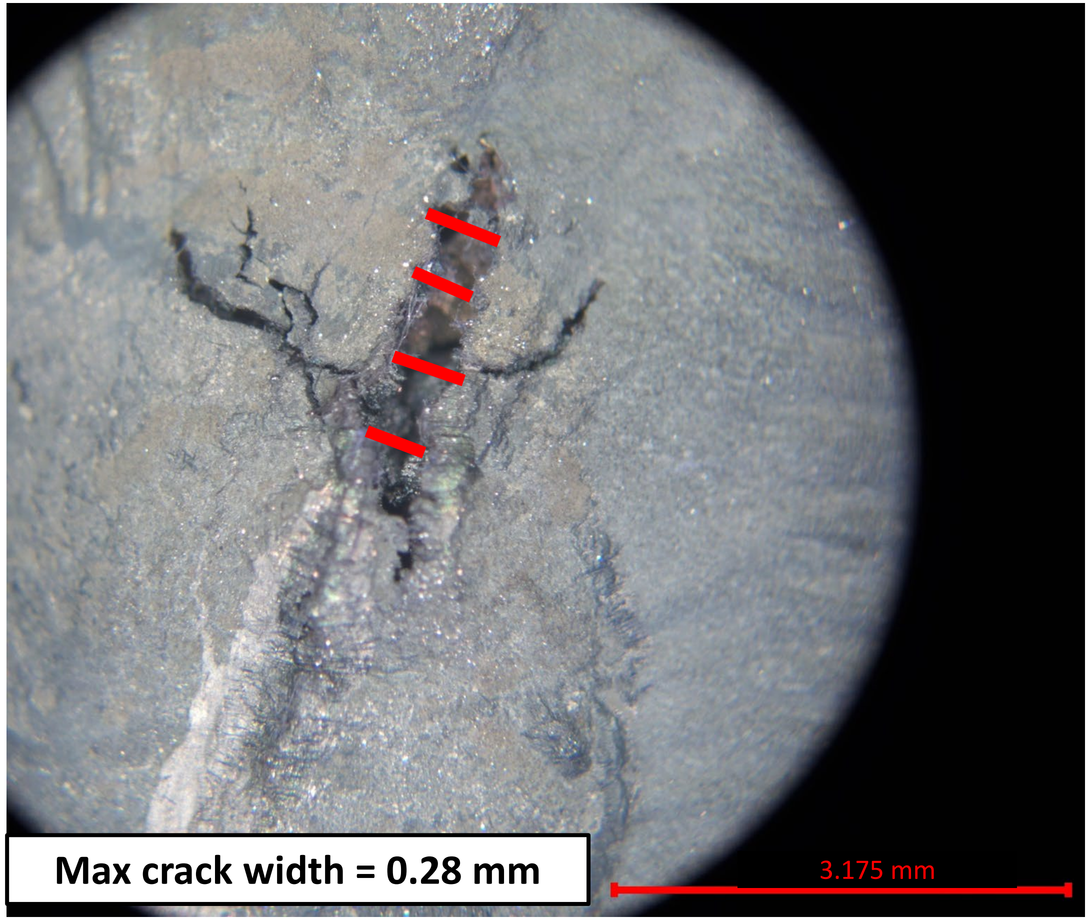



# Weldability numerically assessed by maximum crack length, total crack length, and maximum crack width

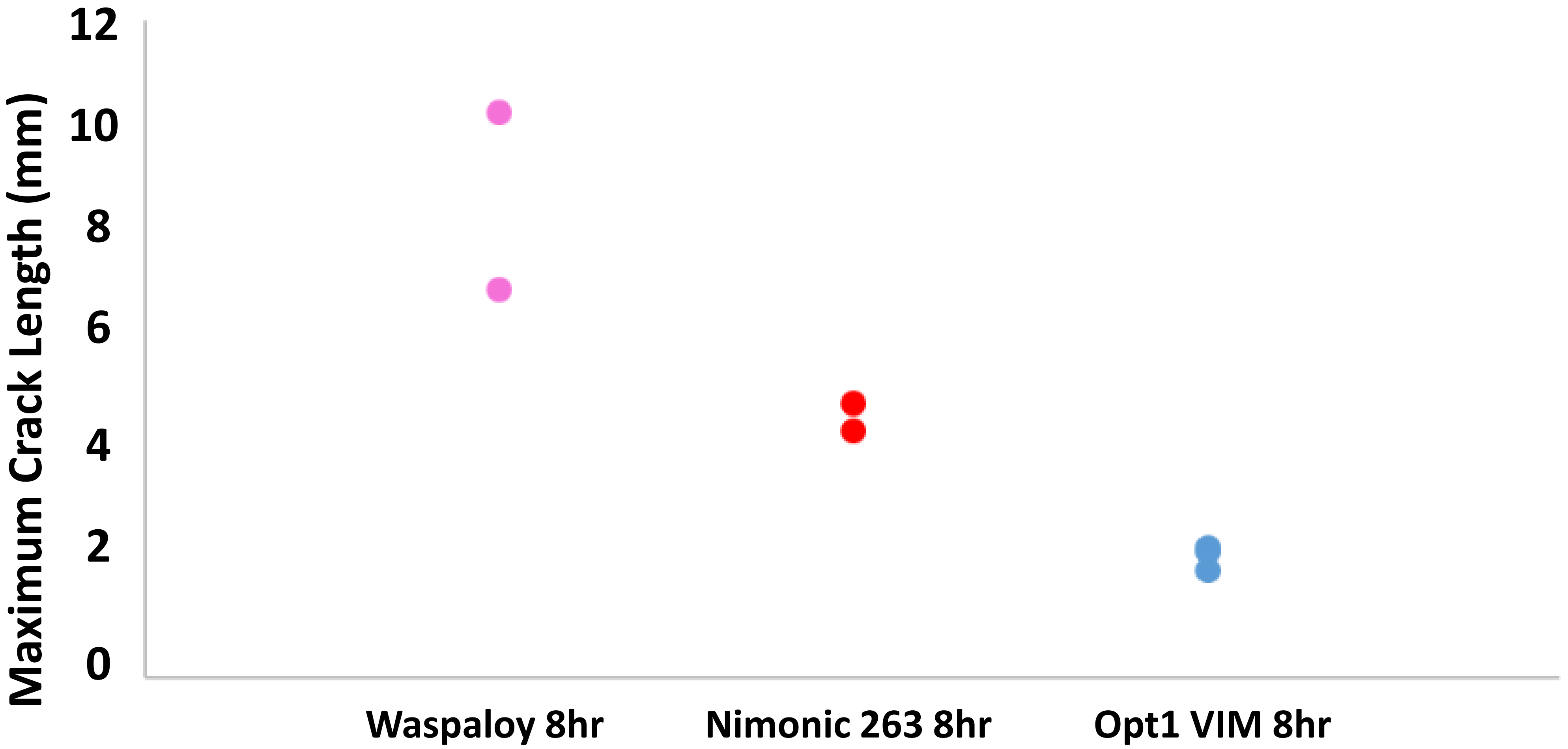
**Crack Length Measurements on Nimonic 263**




**Crack Width Measurements on Nimonic 263**



# Optimized composition weldability outperforms Waspaloy and N263



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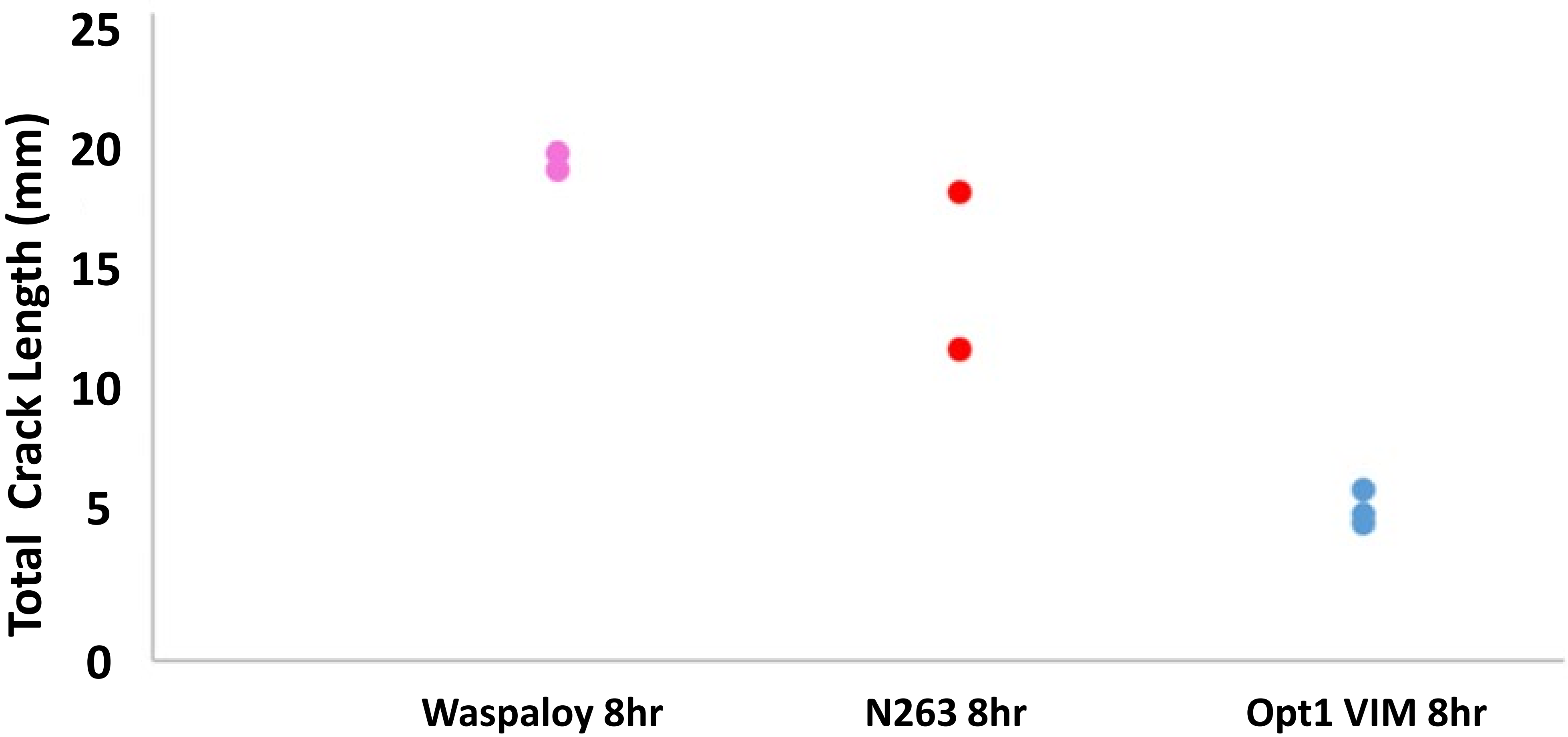

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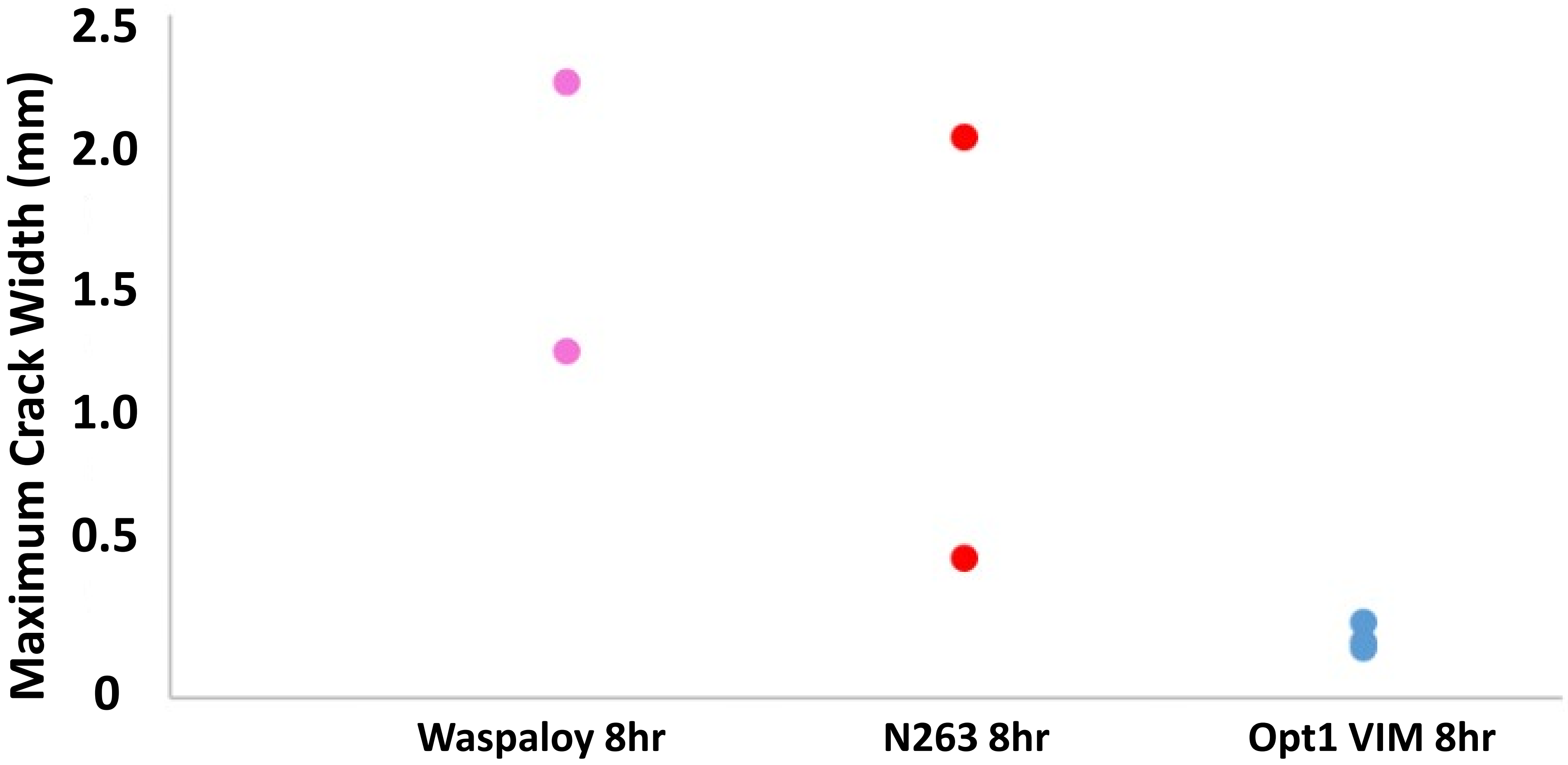
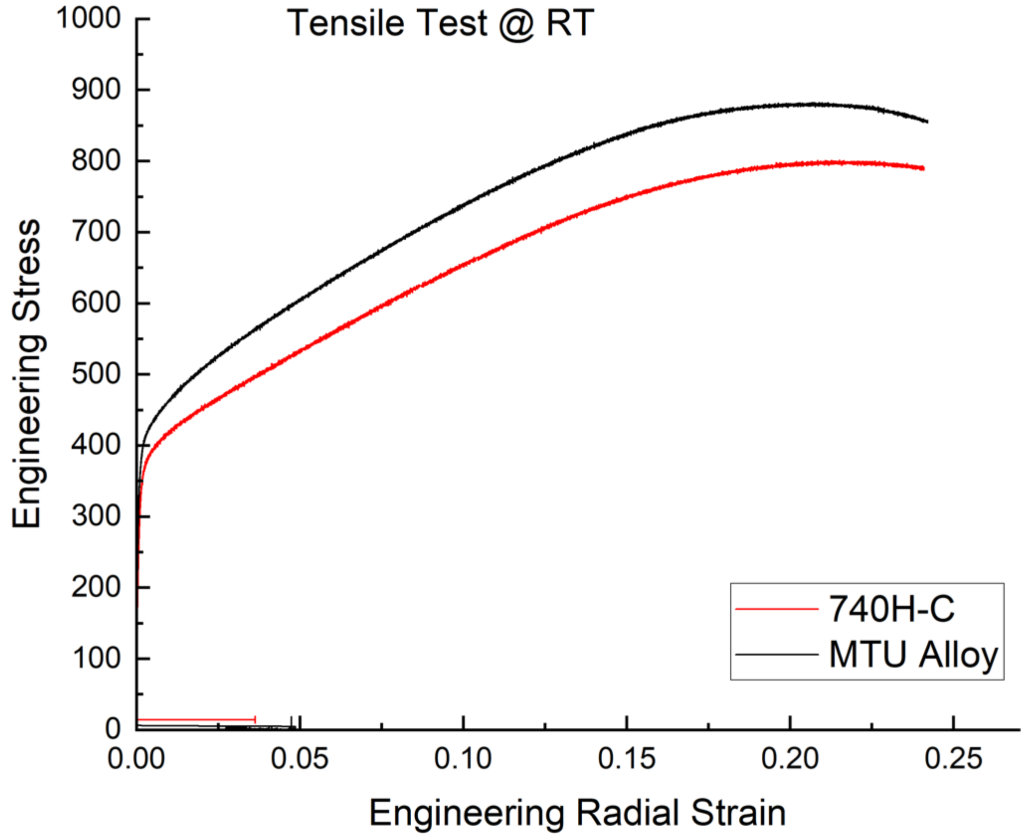
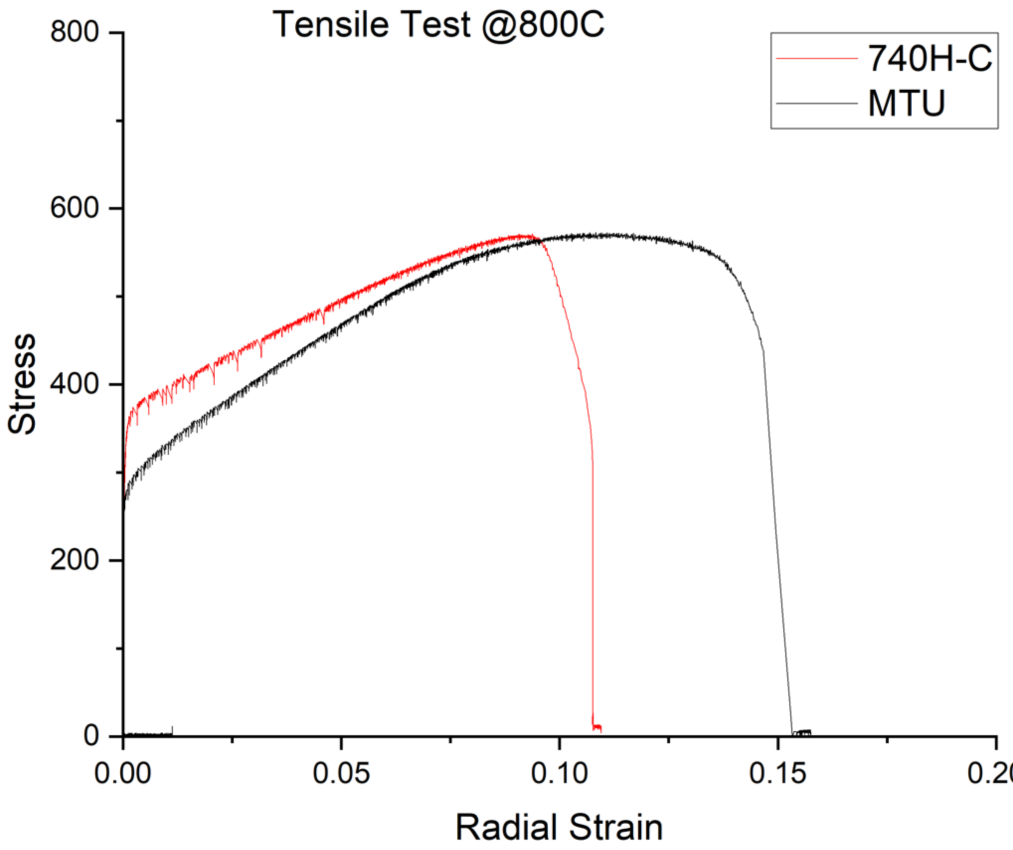
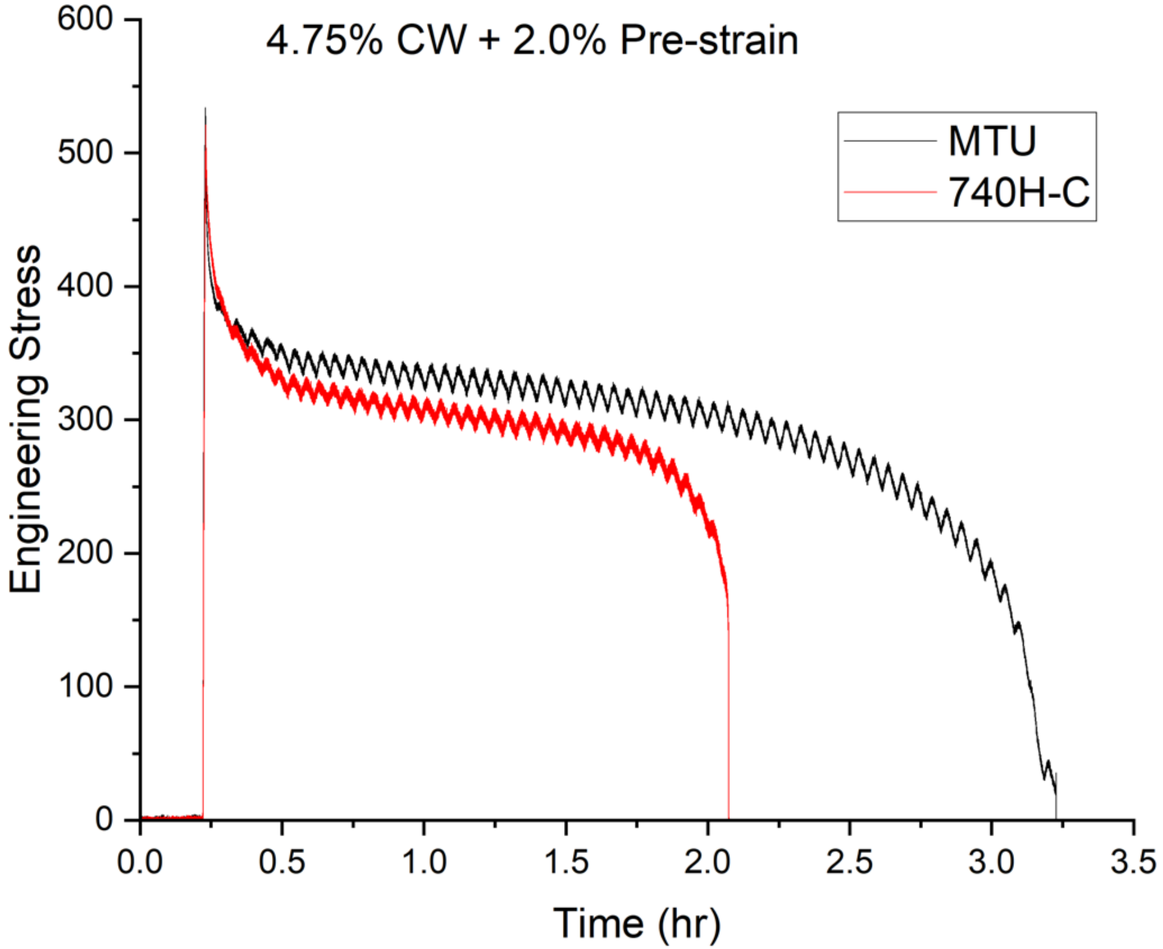


# Initial Gleeble hot tensile tests show Opt1 is competitive with 740-H



# Stress relaxation cracking test shows good initial results - analysis currently in progress




Test conditions:

- 800C
- 4.75% Cold work
- 2.0% pre-strain

# Next Steps

1. Damage analysis on Gleeble testing
2. Creep testing on Opt1
3. Scale up Opt2 & Opt3 for additional material property and weldability testing
4. Explore additional compositions discovered via optimization process

# Conclusions

1. CALPHAD-driven optimization has been used to discover competitive superalloy alloy compositions
2. Small-scale characterization has shown promising material properties (weldability, hardness, modulus) compared to other commercially available alloys
3. All casting and processing performed in-house at Michigan Technological University – only external characterization needed was Gleeble testing

# Thank you for your time!

# Questions?

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Dr. John Shingledecker: jshingledecker@epri.com