

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

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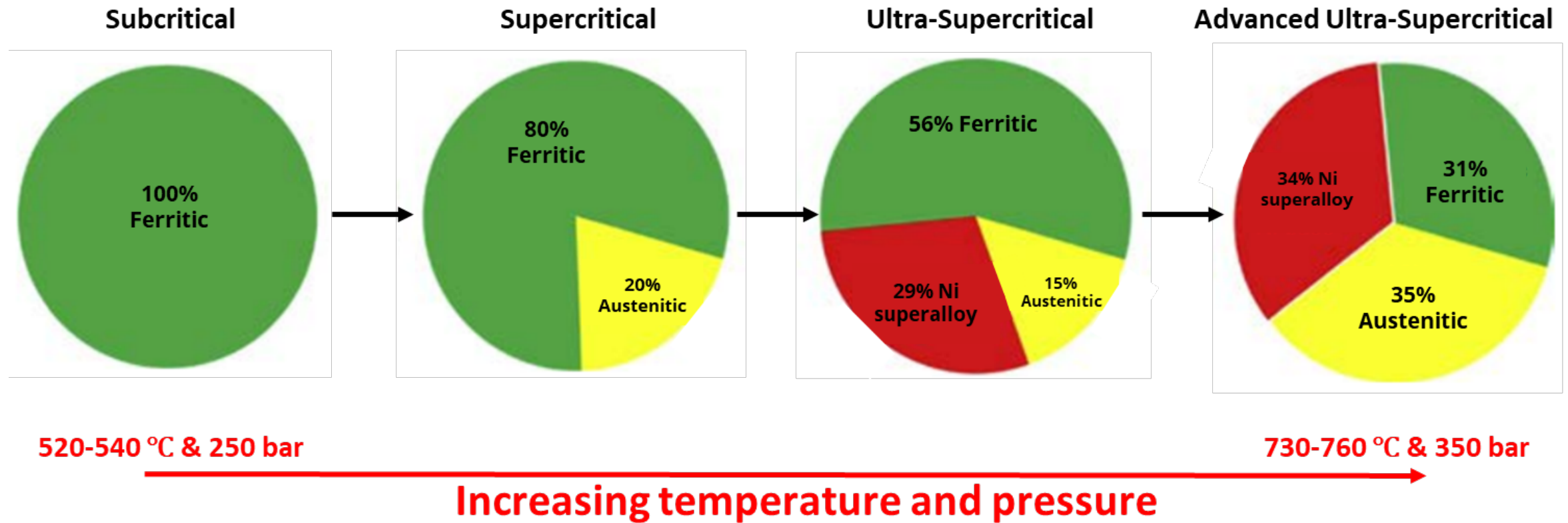
Michigan Technological University
Materials Science
and Engineering



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

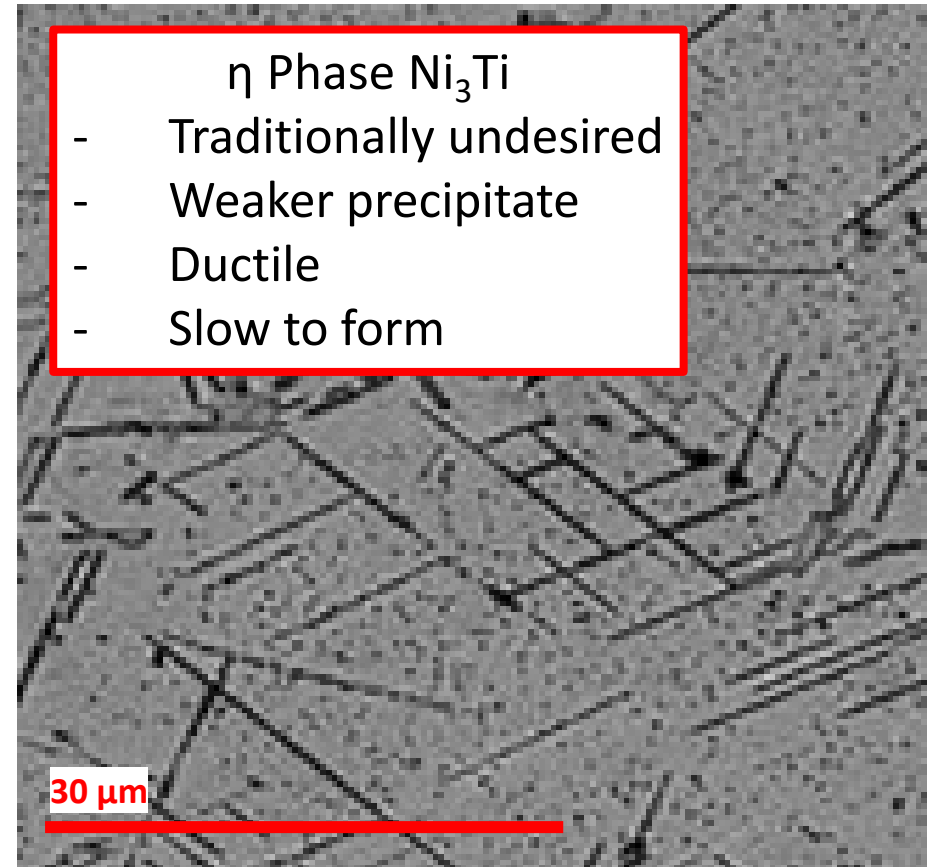
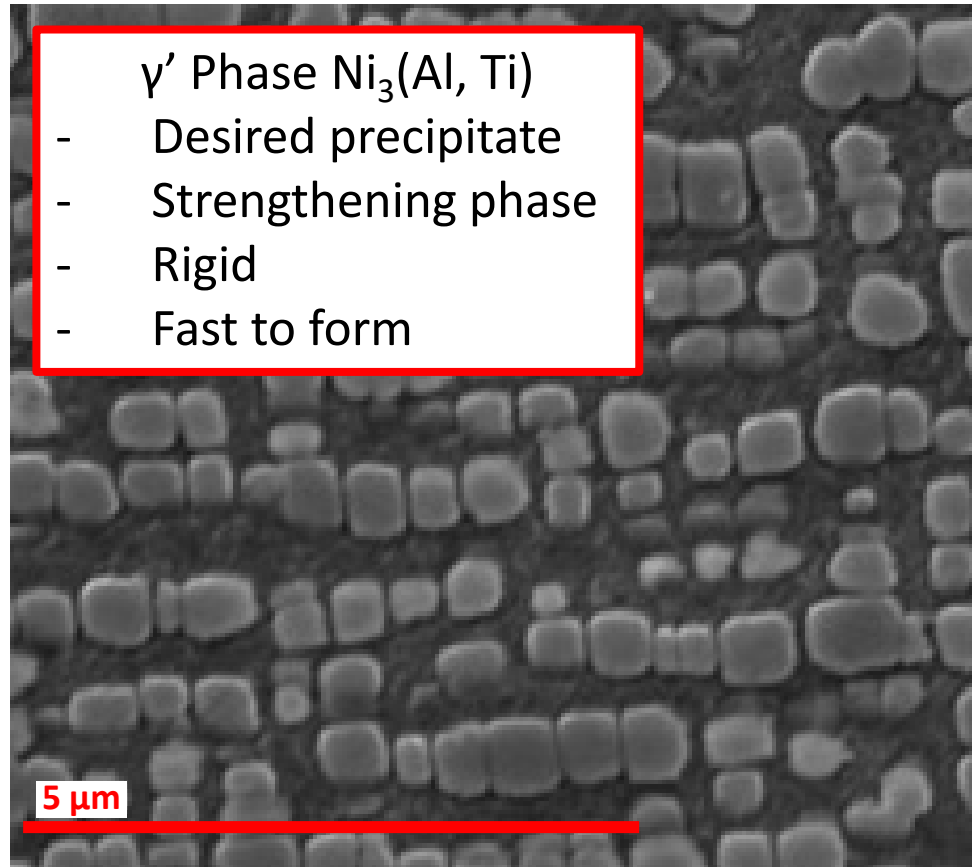
Desire to push to higher temperatures and pressures for efficiency; demands new materials



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



Design space explored previously within TCNI12 CALPHAD database

1 IA H Hydrogen 1.008																	18 VIIIA He Helium 4.002602
3 Li Lithium 6.94	4 IIA Be Beryllium 9.0121831											5 IIIA B Boron 10.81	6 IVA C Carbon 12.011	7 VA N Nitrogen 14.007	8 VIA O Oxygen 15.999	9 VIIA F Fluorine 18.998403163	10 VIII Ne Neon 20.1797
11 Na Sodium 22.98976928	12 IIA Mg Magnesium 24.305	13 IIIB Al Aluminum 26.9815385	14 IIIB Si Silicon 28.085	15 IIIB P Phosphorus 30.973761998	16 IIIB S Sulfur 32.06	17 IIIB Cl Chlorine 35.45	18 IIIB Ar Argon 39.948										
19 K Potassium 39.0983	20 IIA Ca Calcium 40.078	21 IIIB Sc Scandium 44.955908	22 IIIB Ti Titanium 47.867	23 IIIB V Vanadium 50.9415	24 IIIB Cr Chromium 51.9961	25 IIIB Mn Manganese 54.938044	26 IIIB Fe Iron 55.845	27 IIIB Co Cobalt 58.933194	28 IIIB Ni Nickel 58.6934	29 IIIB Cu Copper 63.546	30 IIIB Zn Zinc 65.38	31 IIIB Ga Gallium 69.723	32 IIIB Ge Germanium 72.630	33 IIIB As Arsenic 74.921595	34 IIIB Se Selenium 78.971	35 IIIB Br Bromine 79.904	36 IIIB Kr Krypton 83.798
37 Rb Rubidium 85.4678	38 IIA Sr Strontium 87.62	39 IIIB Y Yttrium 88.90584	40 IIIB Zr Zirconium 91.224	41 IIIB Nb Niobium 92.90637	42 IIIB Mo Molybdenum 95.95	43 IIIB Tc Technetium (98)	44 IIIB Ru Ruthenium 101.07	45 IIIB Rh Rhodium 102.90550	46 IIIB Pd Palladium 106.42	47 IIIB Ag Silver 107.8682	48 IIIB Cd Cadmium 112.414	49 IIIB In Indium 114.818	50 IIIB Sn Tin 118.710	51 IIIB Sb Antimony 121.760	52 IIIB Te Tellurium 127.60	53 IIIB I Iodine 126.90447	54 IIIB Xe Xenon 131.293
55 Cs Caesium 132.90545196	56 IIA Ba Barium 137.327	57 - 71 Lanthanoids	72 IIIB Hf Hafnium 178.49	73 IIIB Ta Tantalum 180.94788	74 IIIB W Tungsten 183.84	75 IIIB Re Rhenium 186.207	76 IIIB Os Osmium 190.23	77 IIIB Ir Iridium 192.217	78 IIIB Pt Platinum 195.084	79 IIIB Au Gold 196.966569	80 IIIB Hg Mercury 200.592	81 IIIB Tl Thallium 204.38	82 IIIB Pb Lead 207.2	83 IIIB Bi Bismuth 208.98040	84 IIIB Po Polonium (209)	85 IIIB At Astatine (210)	86 IIIB Rn Radon (222)
87 Fr Francium (223)	88 IIA Ra Radium (226)	89 - 103 Actinoids	104 IIIB Rf Rutherfordium (261)	105 IIIB Db Dubnium (268)	106 IIIB Sg Seaborgium (269)	107 IIIB Bh Bohrium (270)	108 IIIB Hs Hassium (289)	109 IIIB Mt Meitnerium (278)	110 IIIB Ds Darmstadtium (281)	111 IIIB Rg Roentgenium (282)	112 IIIB Cn Copernicium (285)	113 IIIB Nh Nihonium (286)	114 IIIB Fl Flerovium (289)	115 IIIB Mc Moscovium (289)	116 IIIB Lv Livermorium (293)	117 IIIB Ts Tennessine (294)	118 IIIB Og Oganesson (294)
57 La Lanthanum 138.90547	58 Ce Cerium 140.196	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93033	68 Er Erbium 167.259	69 Tm Thulium 168.93422	70 Yb Ytterbium 173.045	71 Lu Lutetium 174.9668			
89 Ac Actinium (227)	90 Th Thorium 232.0377	91 Pa Protactinium 231.03688	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (260)			

Major constituents (>15wt%):

- Ni, Cr

Minor constituents (<15wt%):

- Co, Mo

Precipitate formers (<3wt%):

- Al, Ti

Other elements tested and not selected:

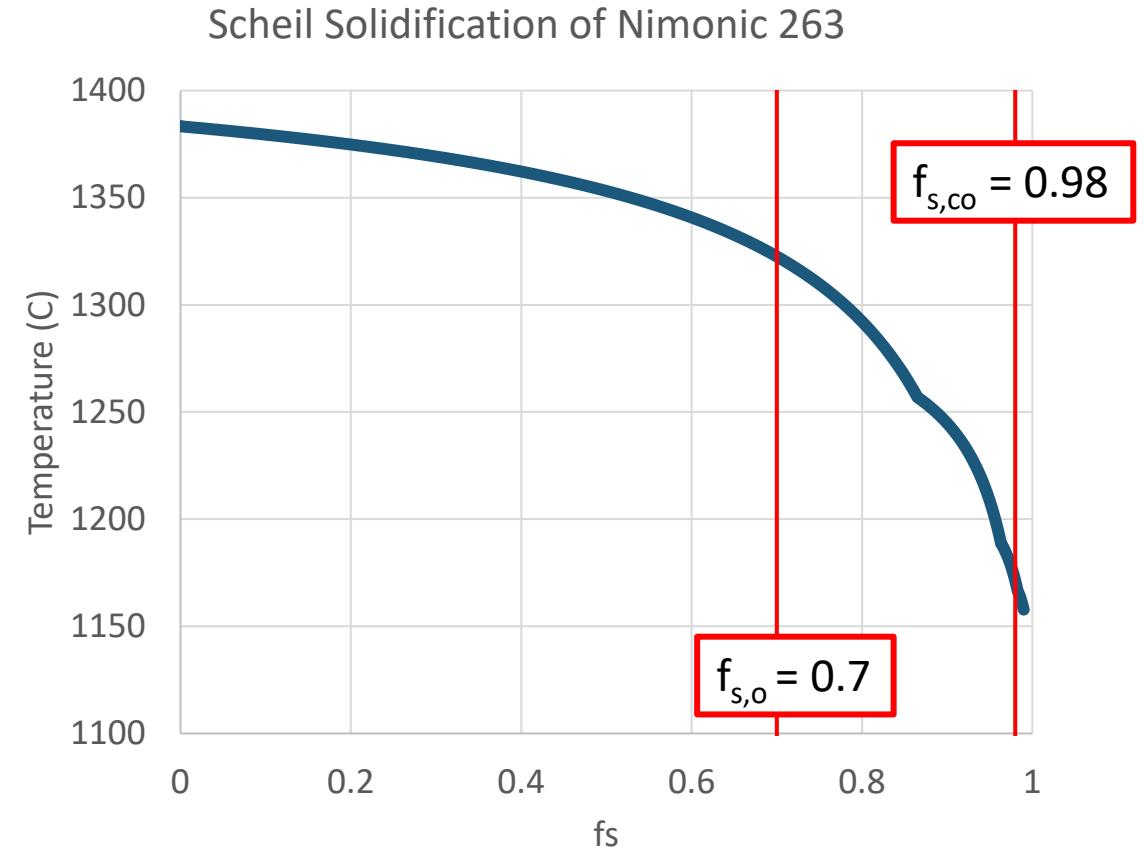
- V, Fe, Nb, W

Solidification cracking resistance assessed via CALPHAD Scheil calculation

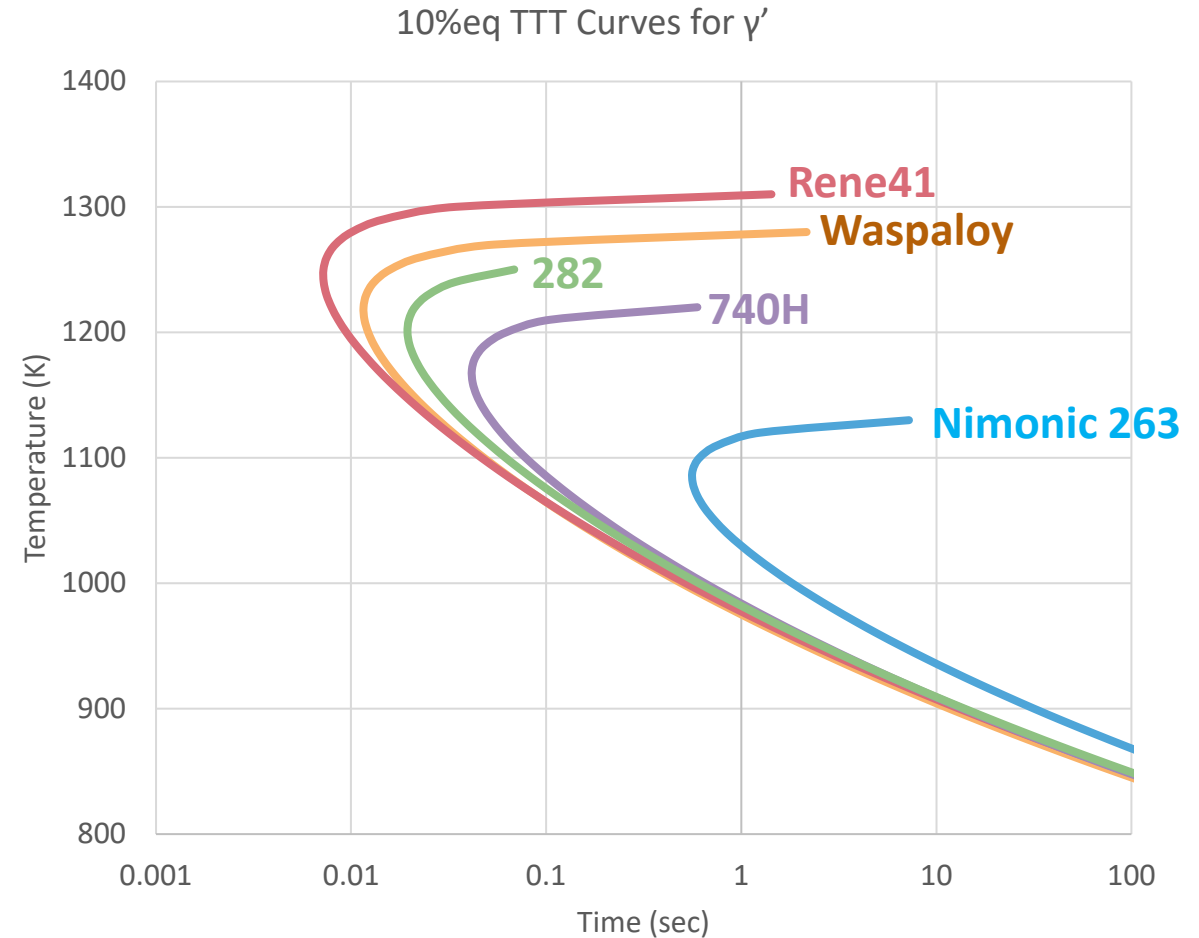
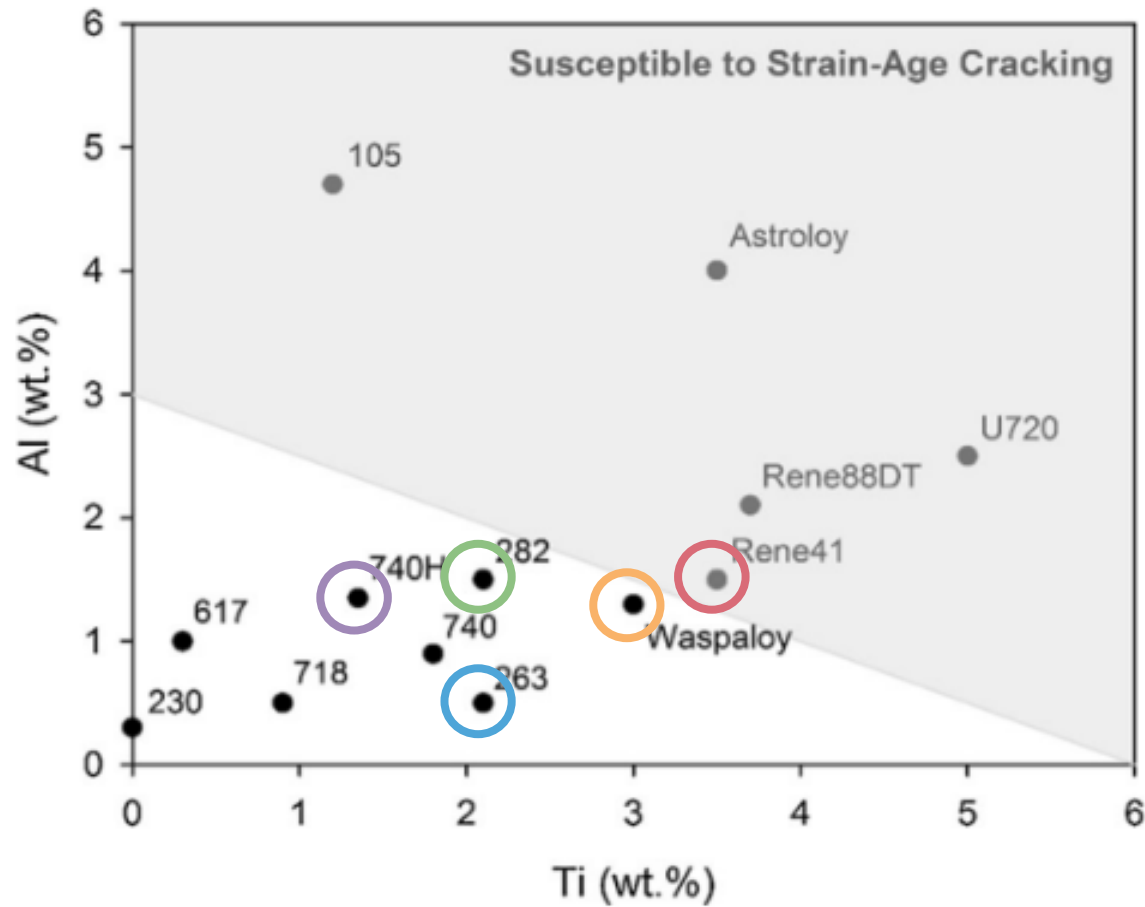
- Last year demonstrated limitations with automation in Kou cracking model
- Favored Easton hot tearing model
- Both are now featured & automated within ThermoCalc package!

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

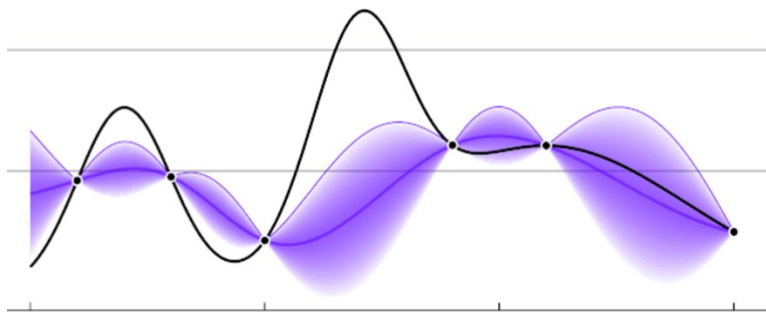
$$Score_{Easton.Solid} = \int_{T_0}^{T_{co}} f_s(T) dT$$



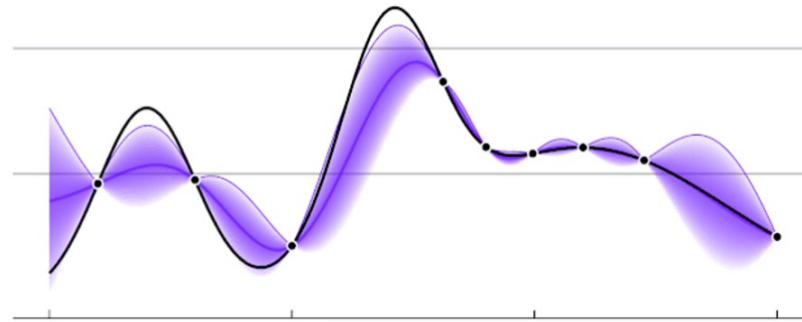
Strain-age cracking resistance correlated with slower γ' kinetics



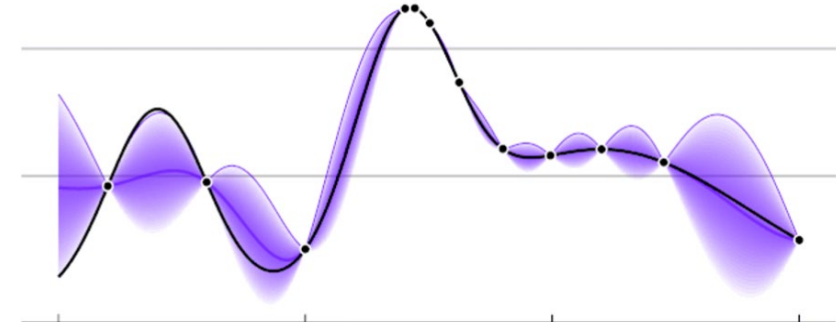
Utilize Bayesian Optimization to efficiently optimize simulated material properties



Initial BO does not find maxima



More calculations reduce uncertainty



Efficiently locate maxima

Explore high variance regions
Exploit high reward regions

Best optimized alloys for small-scale testing

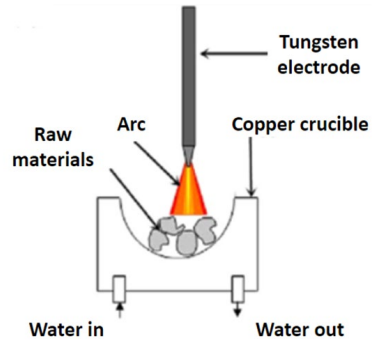
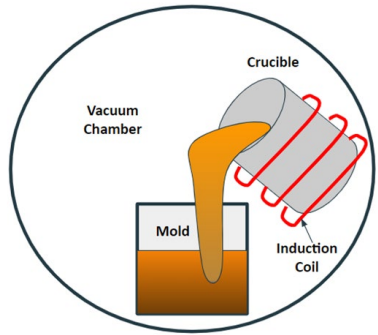
Rank	Co	Cr	Mo	Al	Ti	C	Ni
Opt1	5.0	18.6	9.9	0.53	2.37	0.06	63.53
Opt2	5.0	18.5	5.17	0.64	2.91	0.07	67.71
Opt3	9.5	18.5	5.07	0.73	3.77	0.07	62.34
Nimonic 263	20.5	19.9	5.7	0.27	2.1	0.07	51.46

All in wt%



Sample Creation/Processing Map

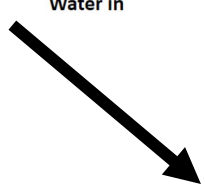
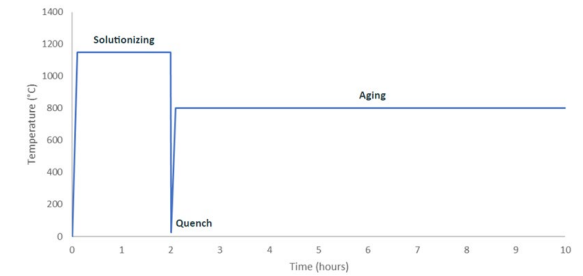
Vacuum Induction Melting (VIM) or Arc Melting



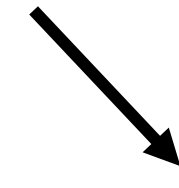
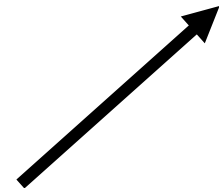
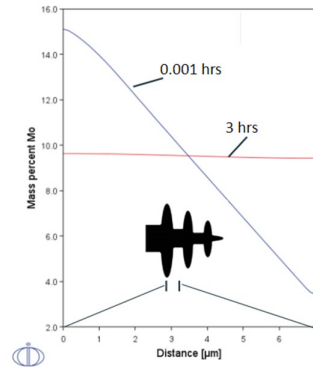
Forging



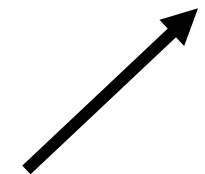
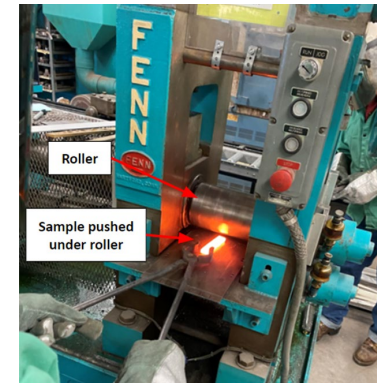
Heat Treating



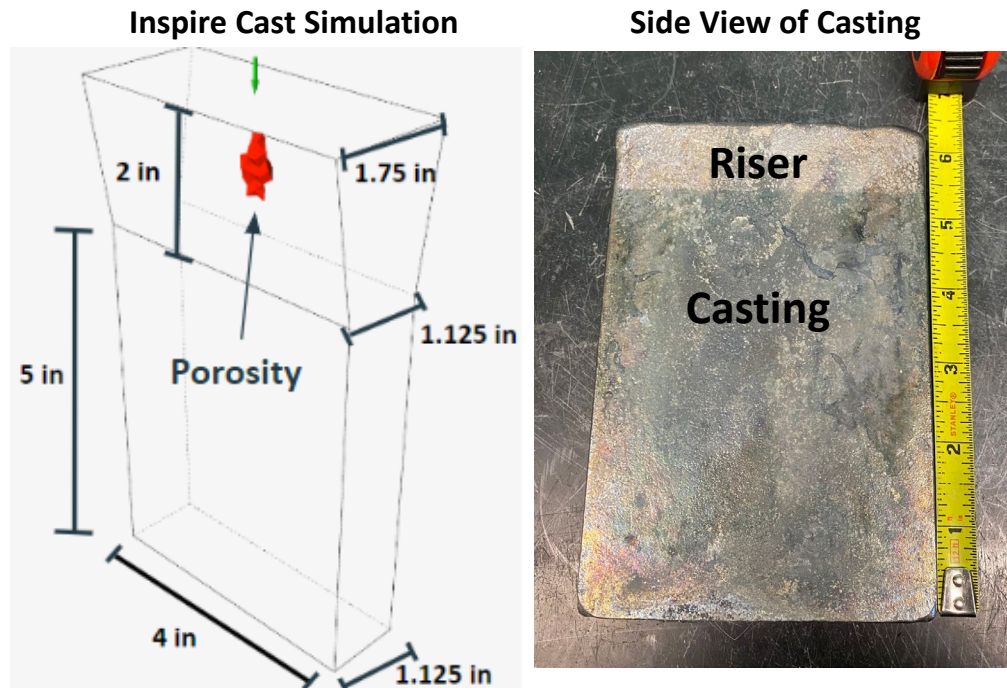
Homogenization



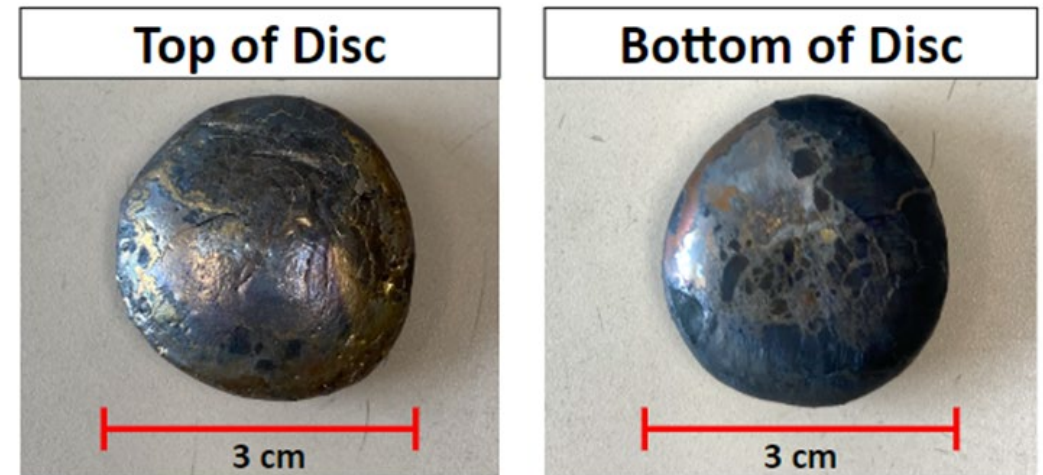
Hot Rolling



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



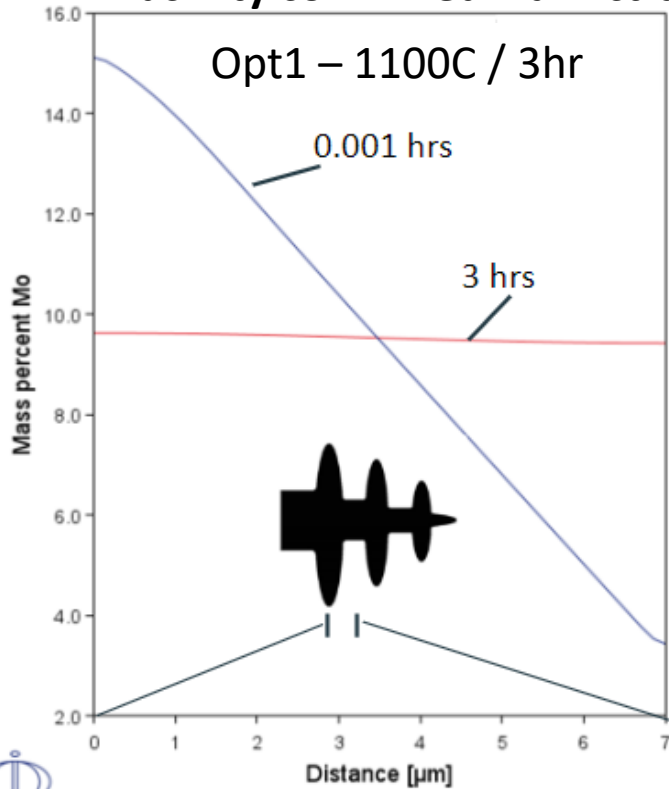
VIM melts only for Opt1



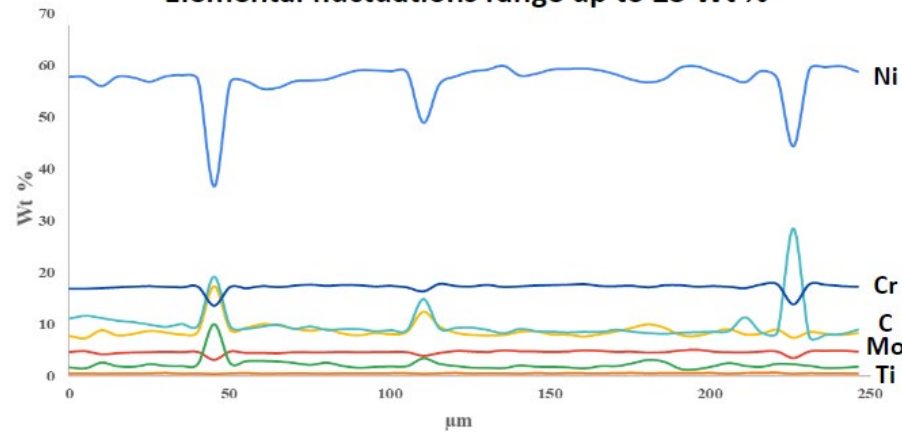
Arc Melts for Opt1, 2, 3

Homogenization performed with N263 process successfully

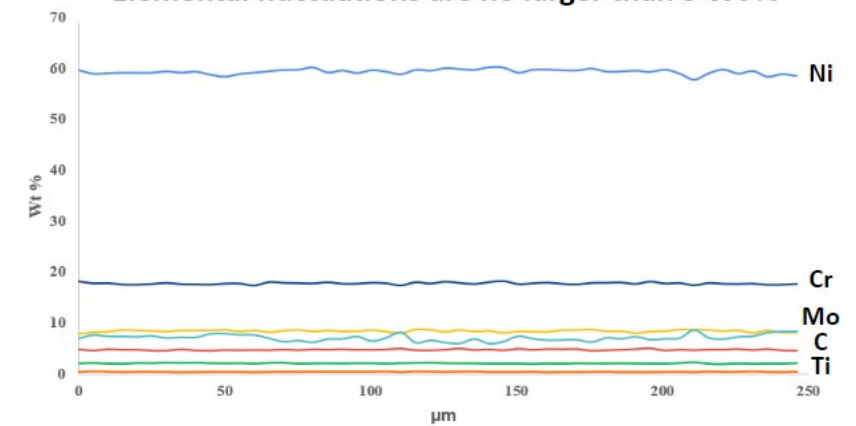
Diffusivity confirmed via Dictra



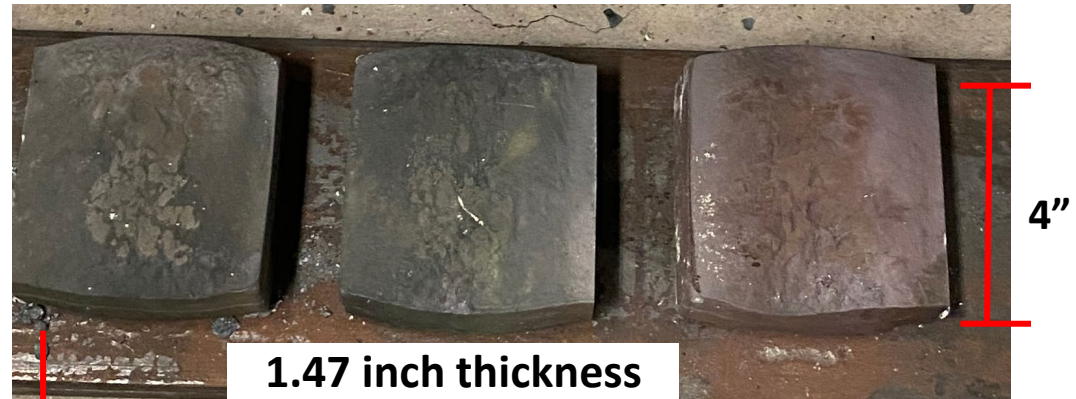
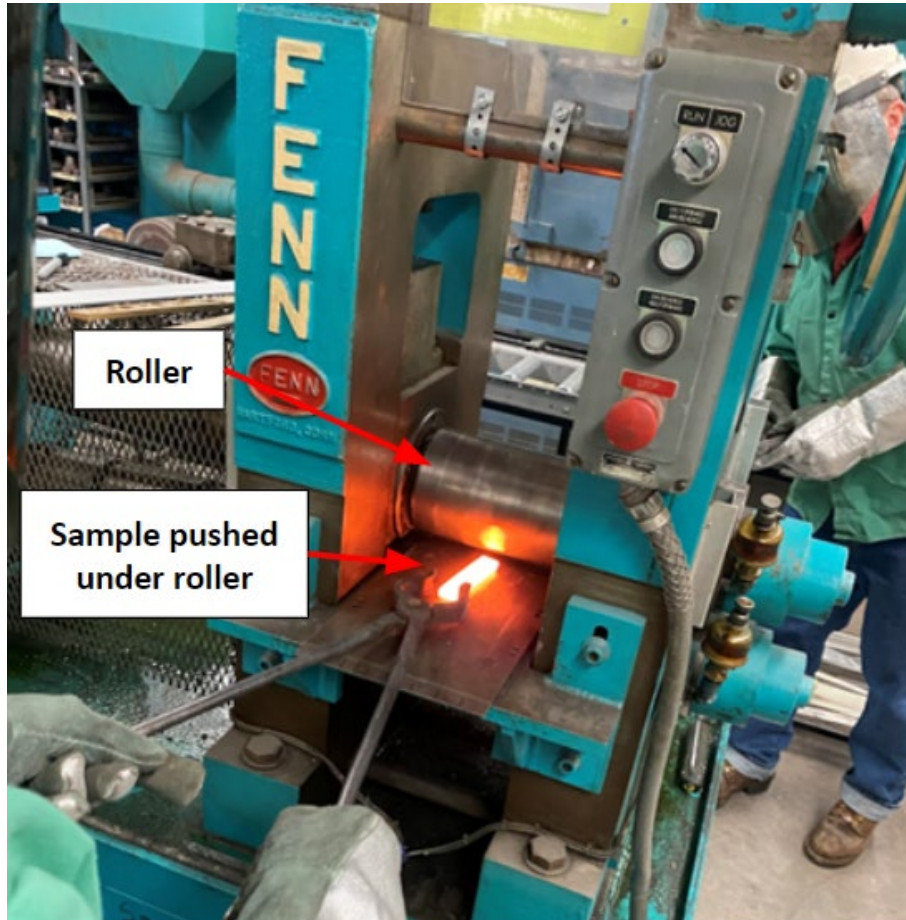
Elemental fluctuations range up to 23 Wt %



Elemental fluctuations are no larger than 3 Wt %

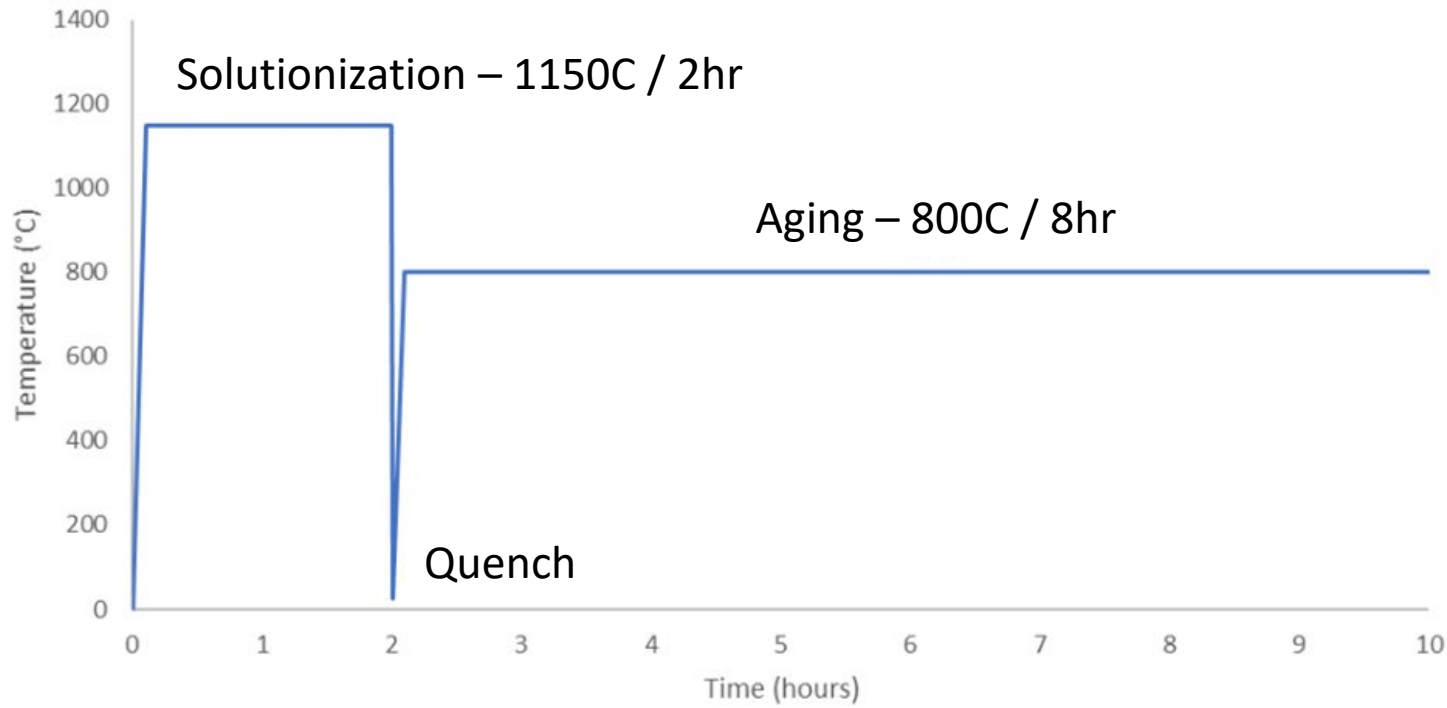


In-house forging and hot rolling on all VIM/Arc samples



Heat treatment varied to explore standard and over-aged conditions

Standard Nimonic 263 Heat Treatment



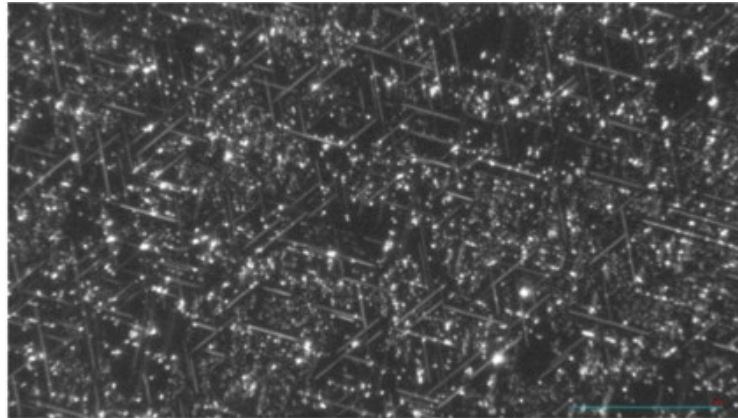
Aging Treatment

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

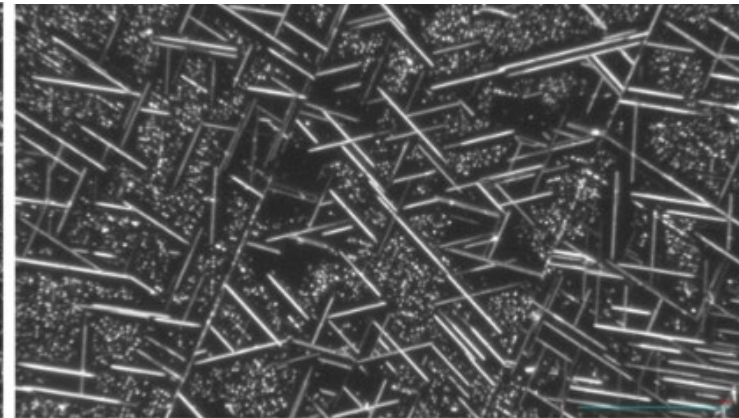


Optical microscopy and point counting used for volume fraction analysis

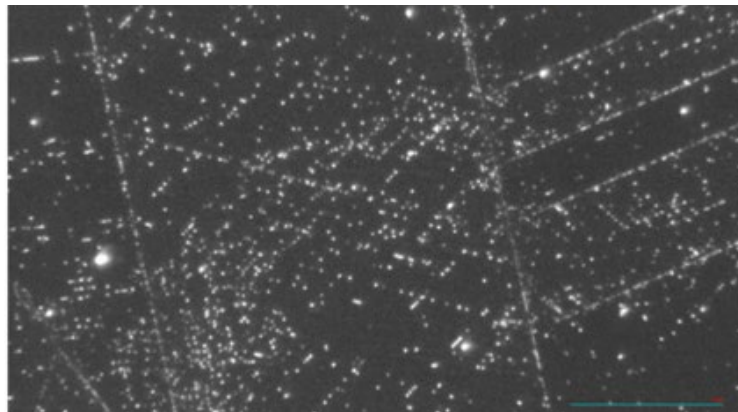
Opt1 – 800C / 1000hr



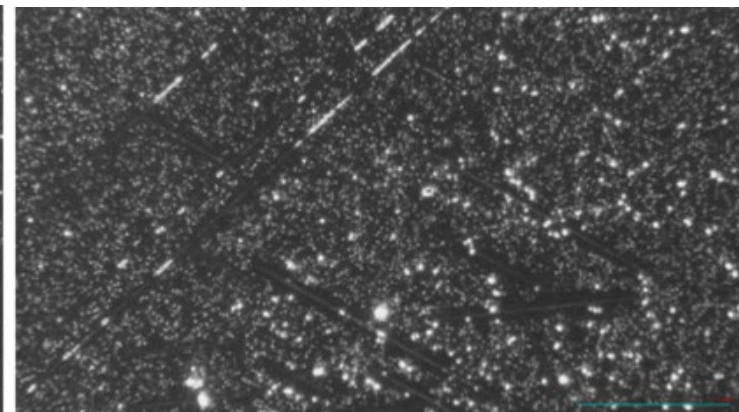
Opt1 – 850C / 1000hr



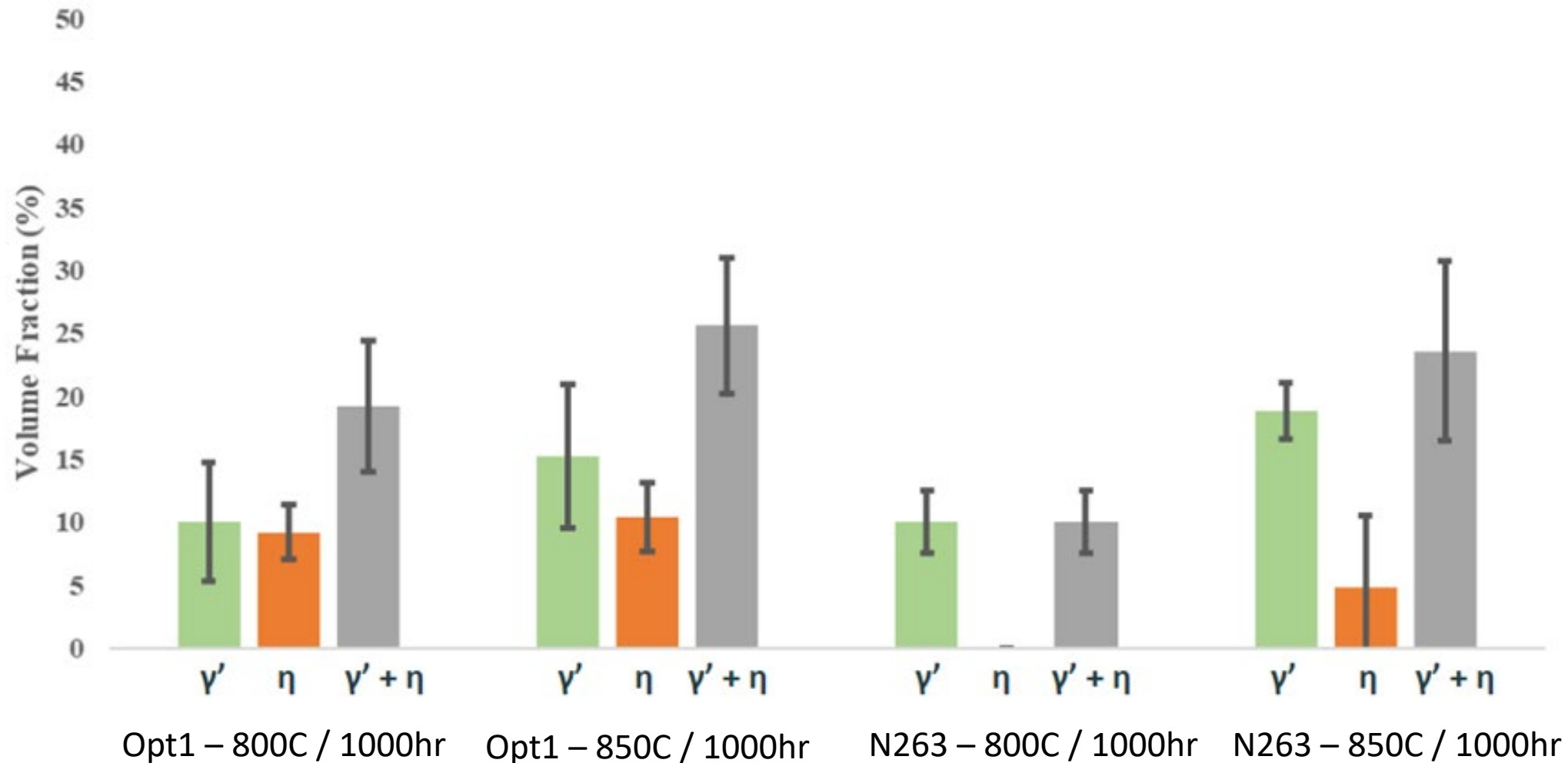
N263 – 800C / 1000hr



N263 – 850C / 1000hr

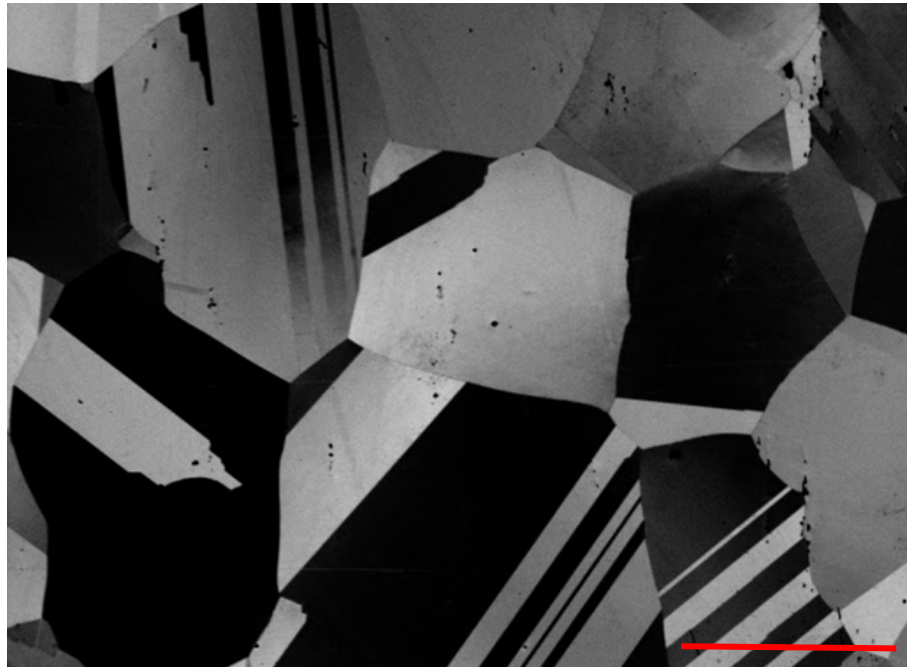


Optimized samples have higher η volume fractions and comparable γ'



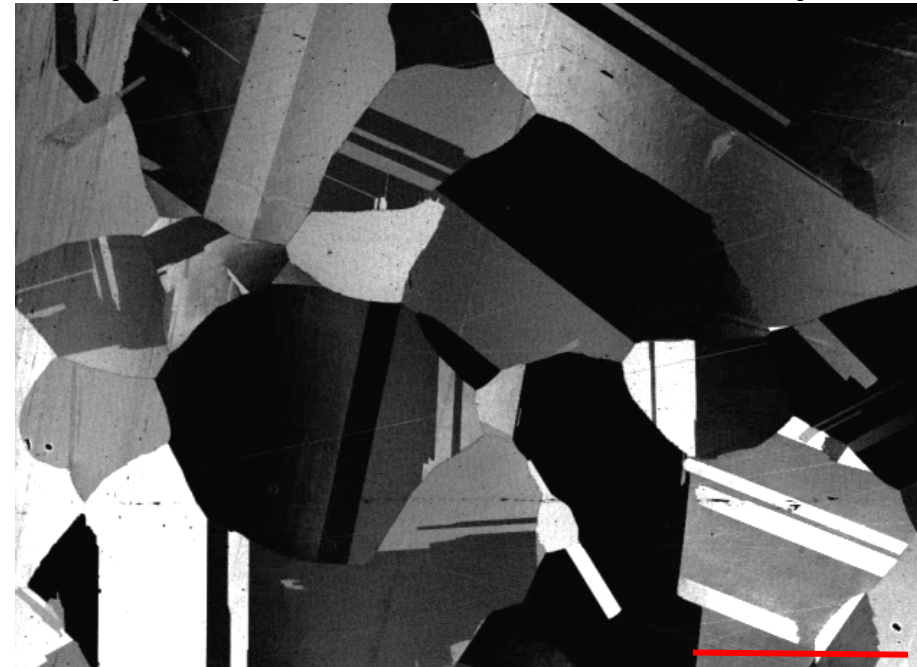
Grain sizes between samples are comparable across tested heat treatments

N263 – 800C / 8hr $d = 230 \pm 10 \mu\text{m}$



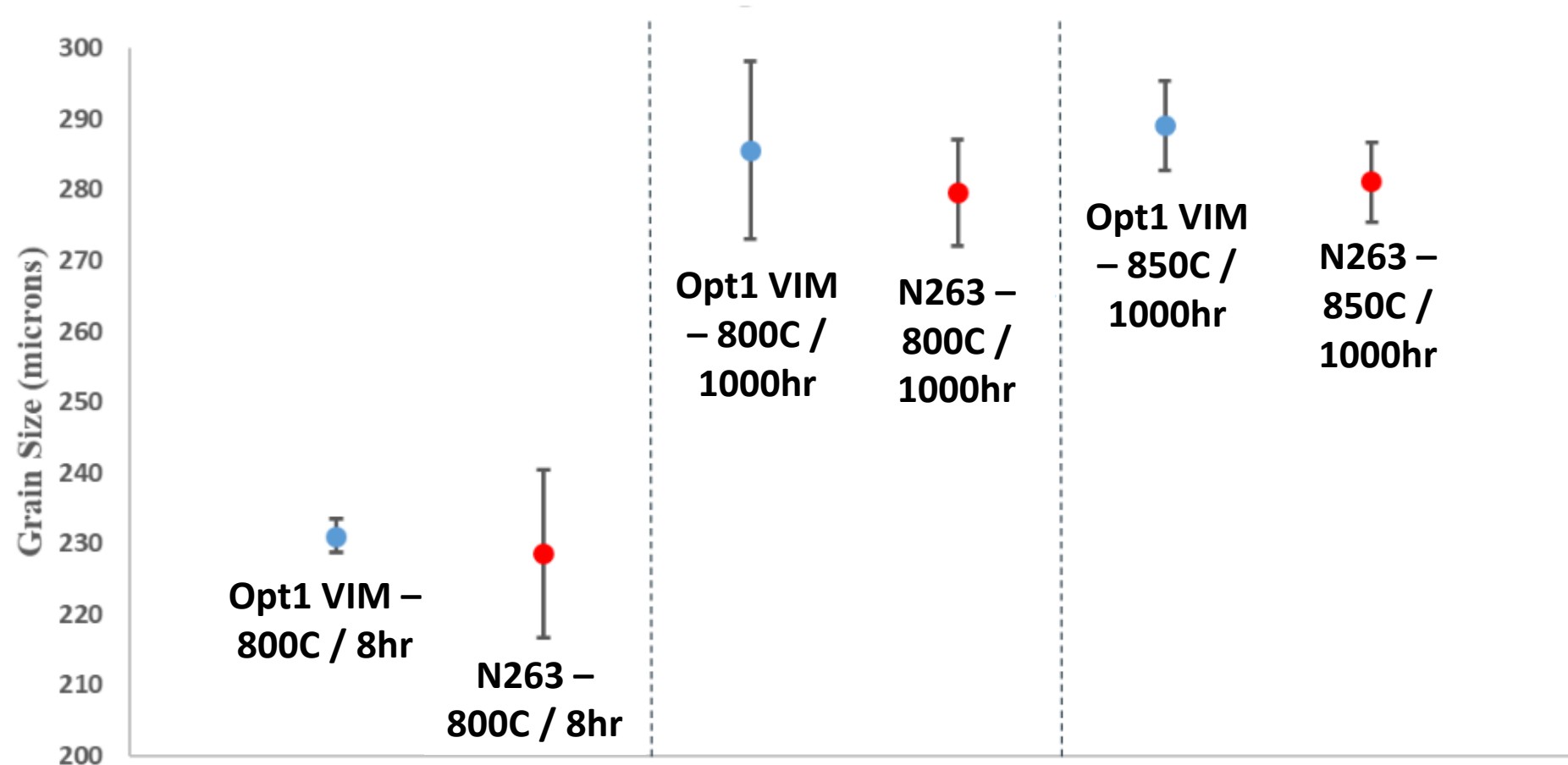
250 μm

Opt1 VIM – 800C / 8hr $d = 231 \pm 2 \mu\text{m}$

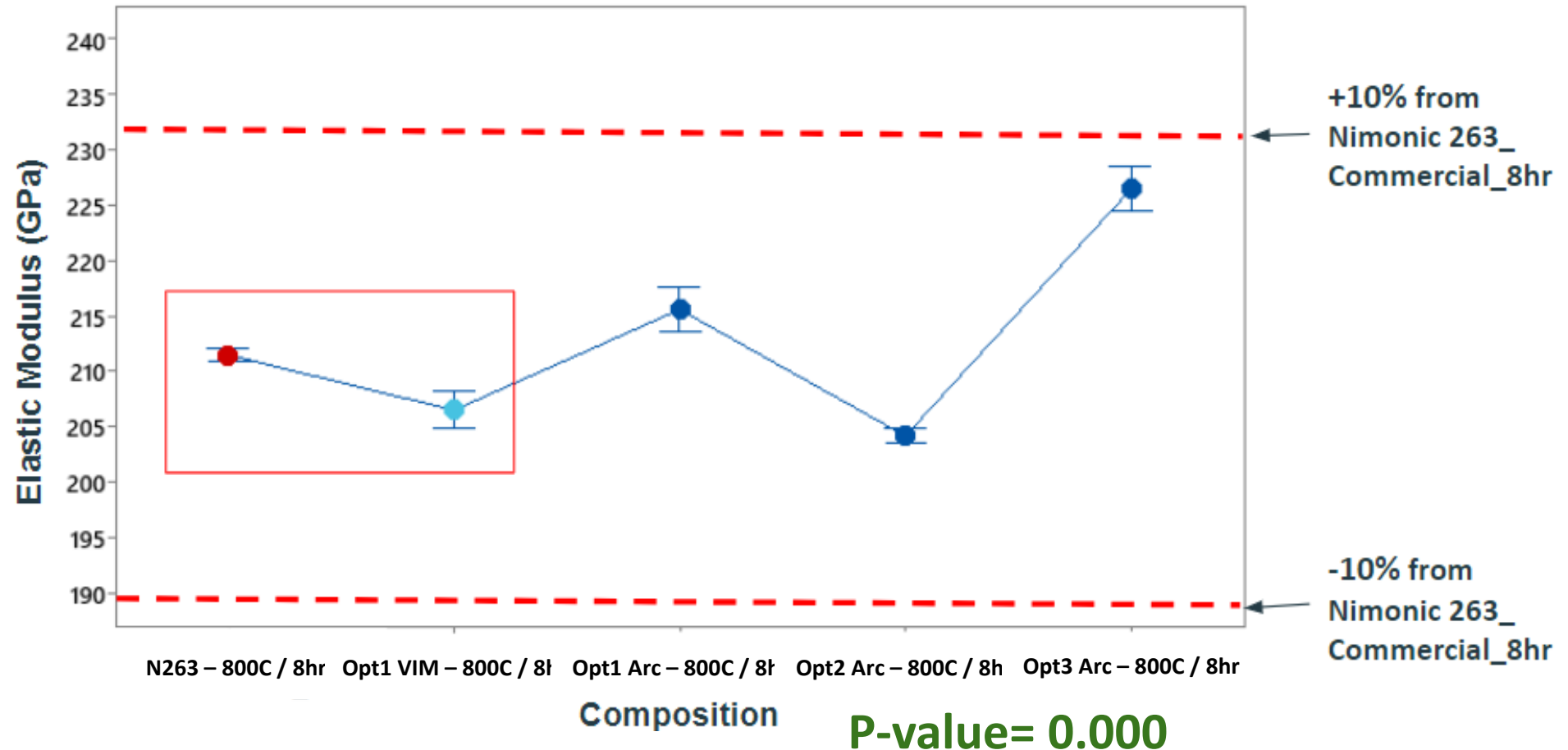


250 μm

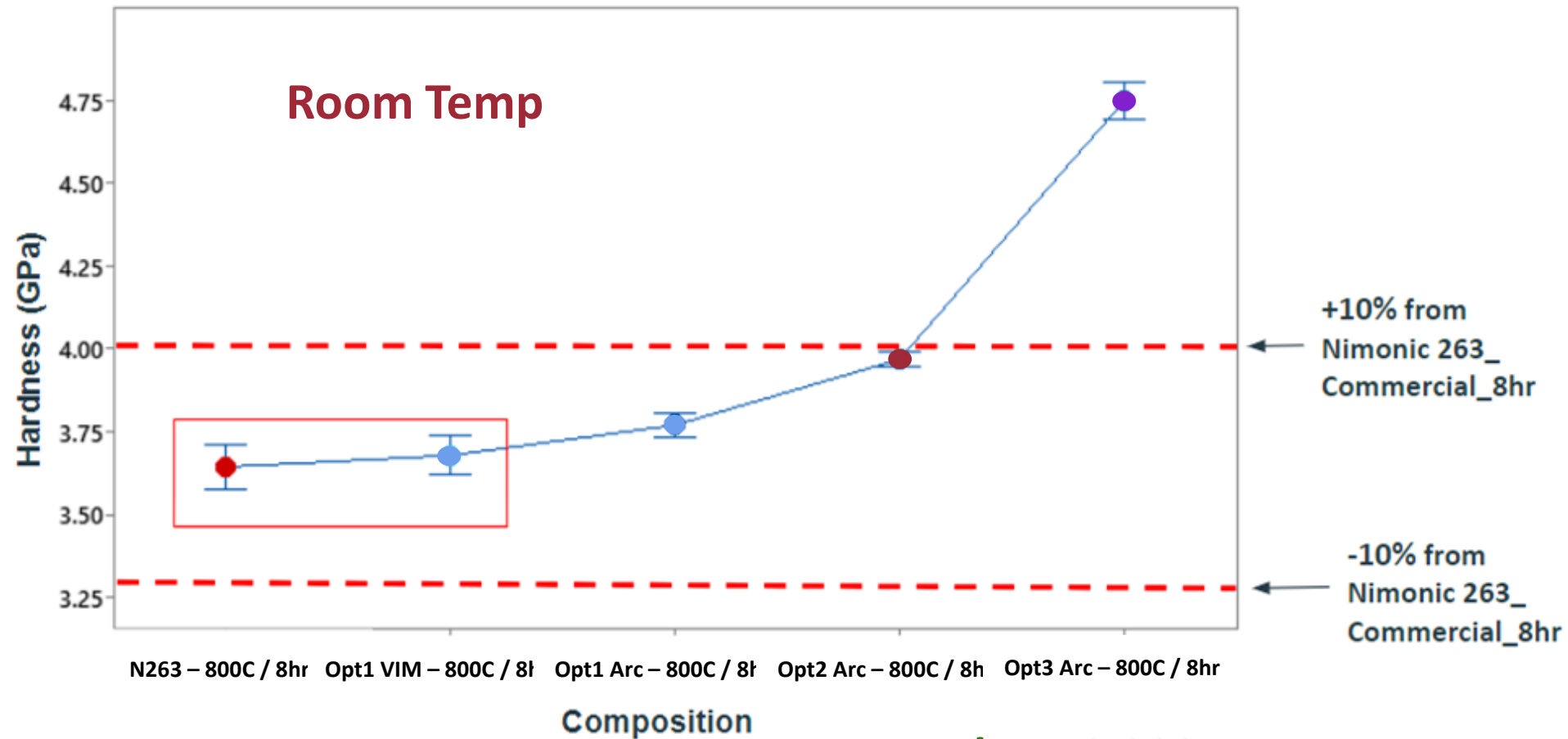
Grain sizes between samples are comparable across tested heat treatments



Elastic moduli show variance but are all within desired range

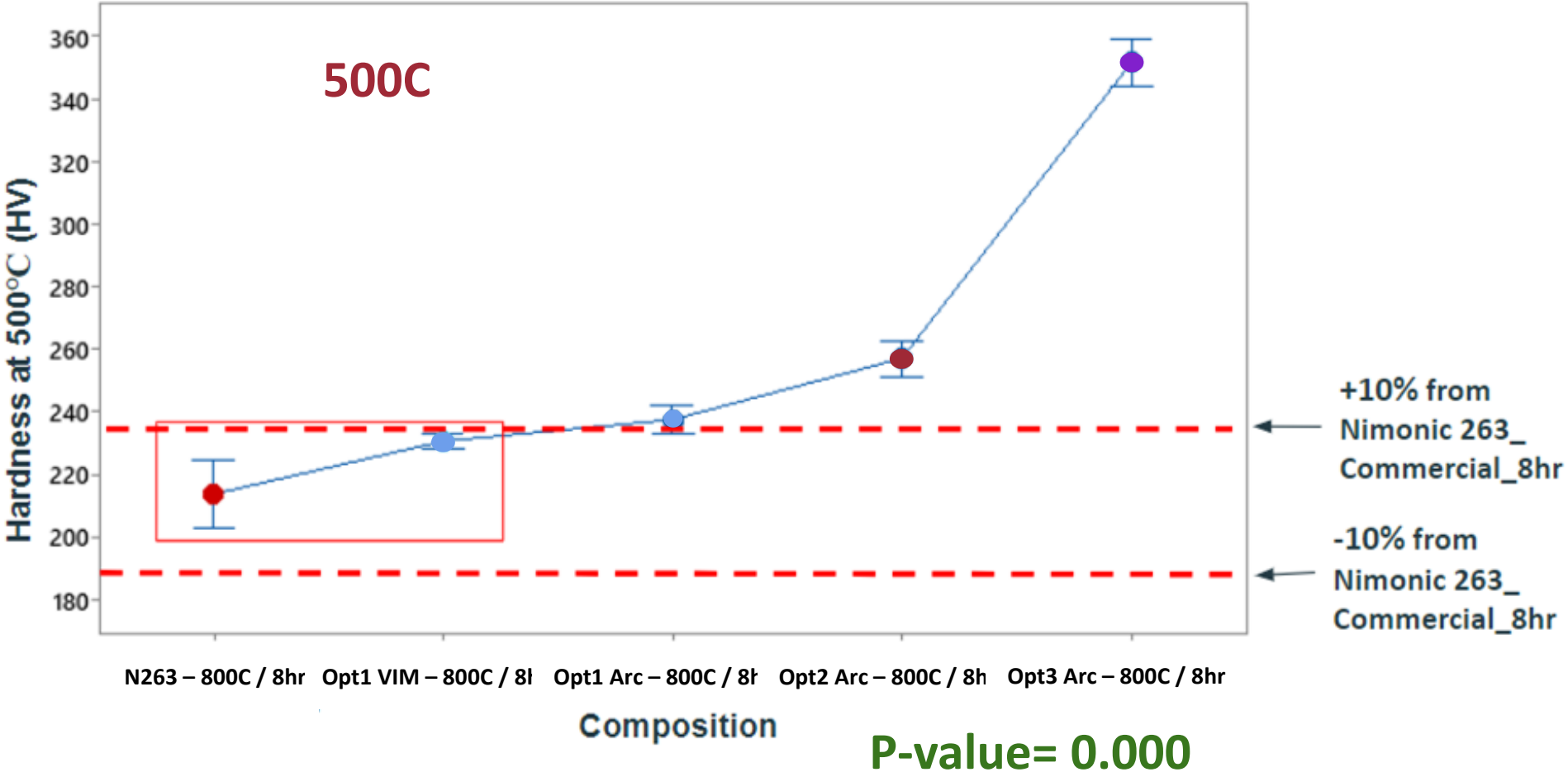


Opt3 composition exhibits with significant RT hardness that other samples

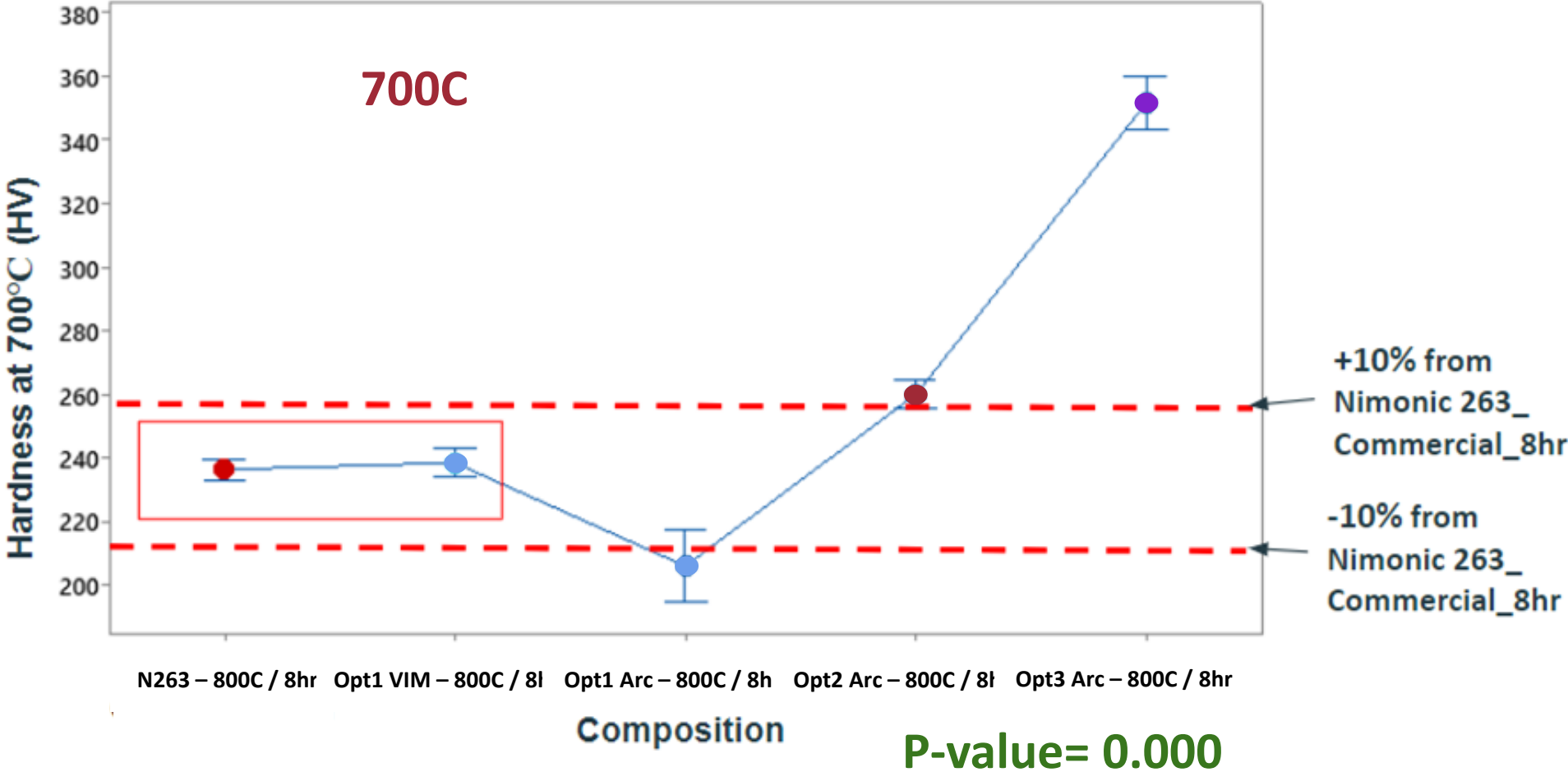


P-value= 0.000

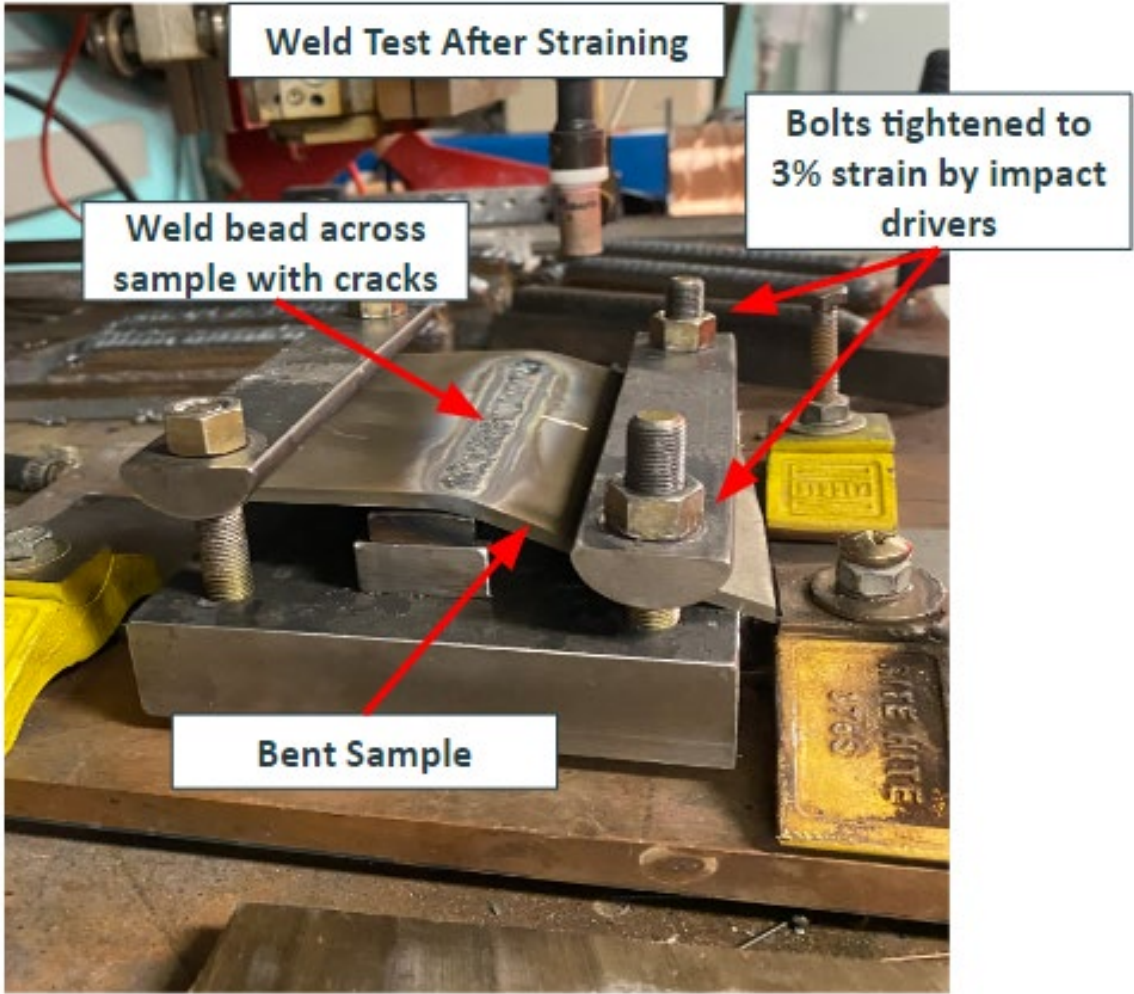
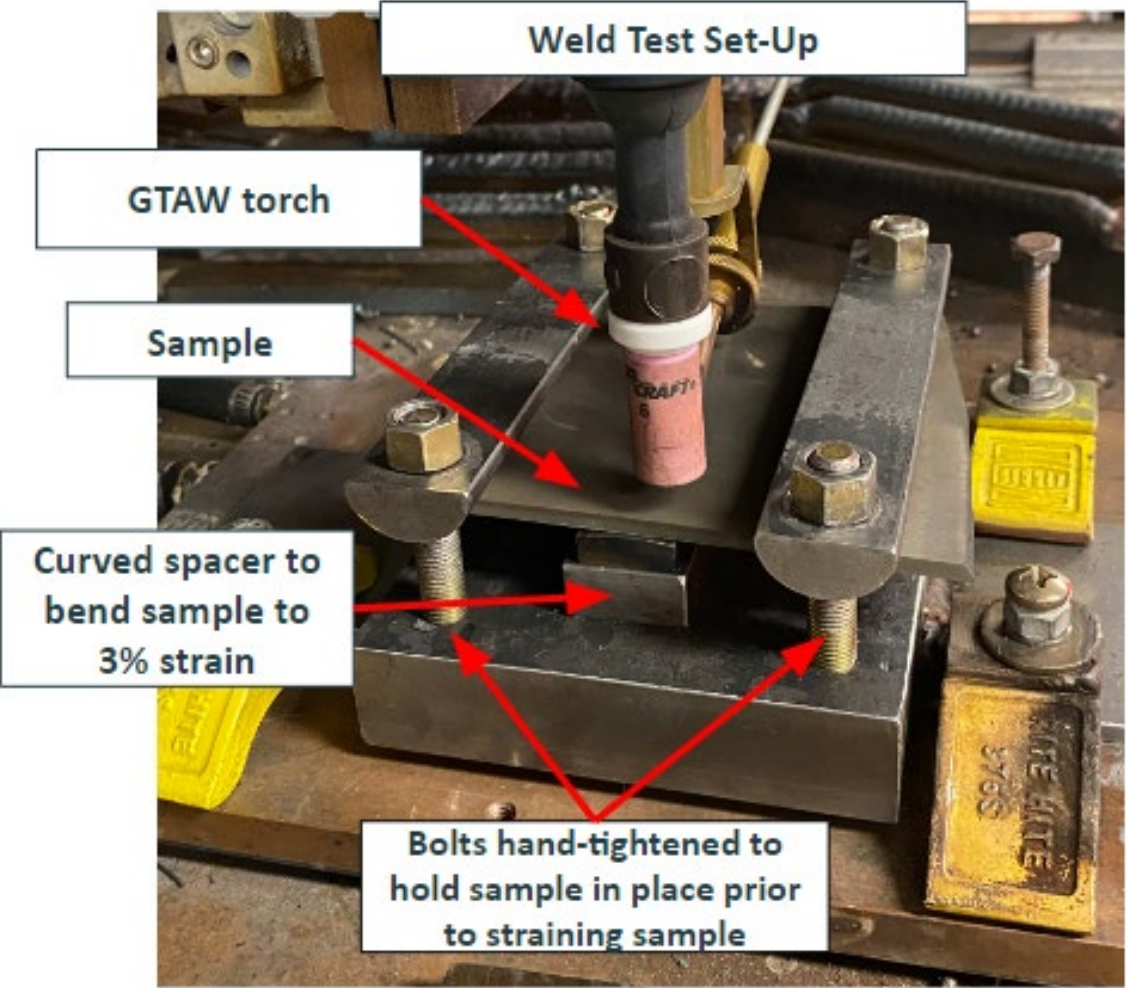
As temperature increases, optimized alloys perform better than N263



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

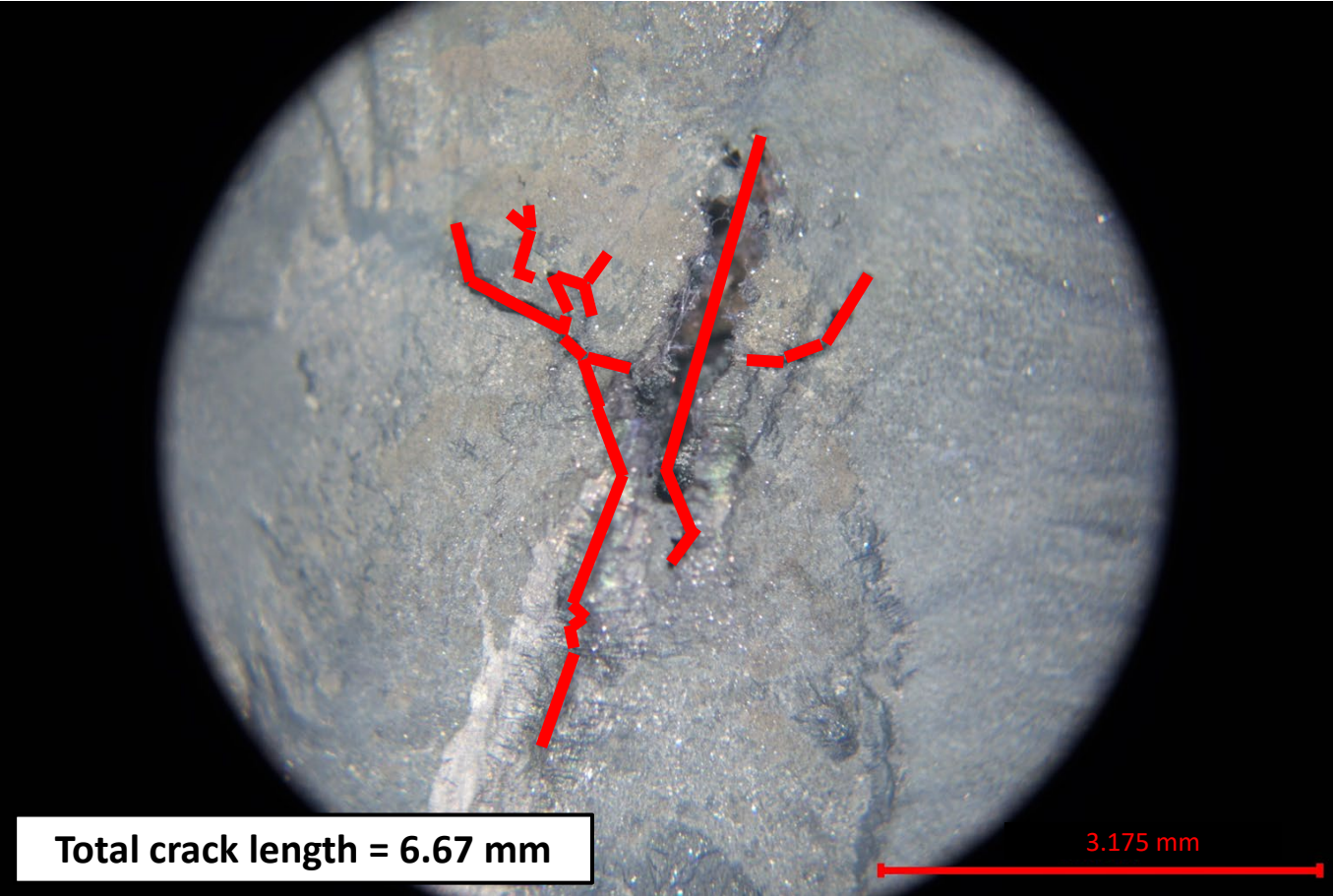


Trans-Varestraint weldability test rig created in-house at Michigan Tech to test solidification cracking

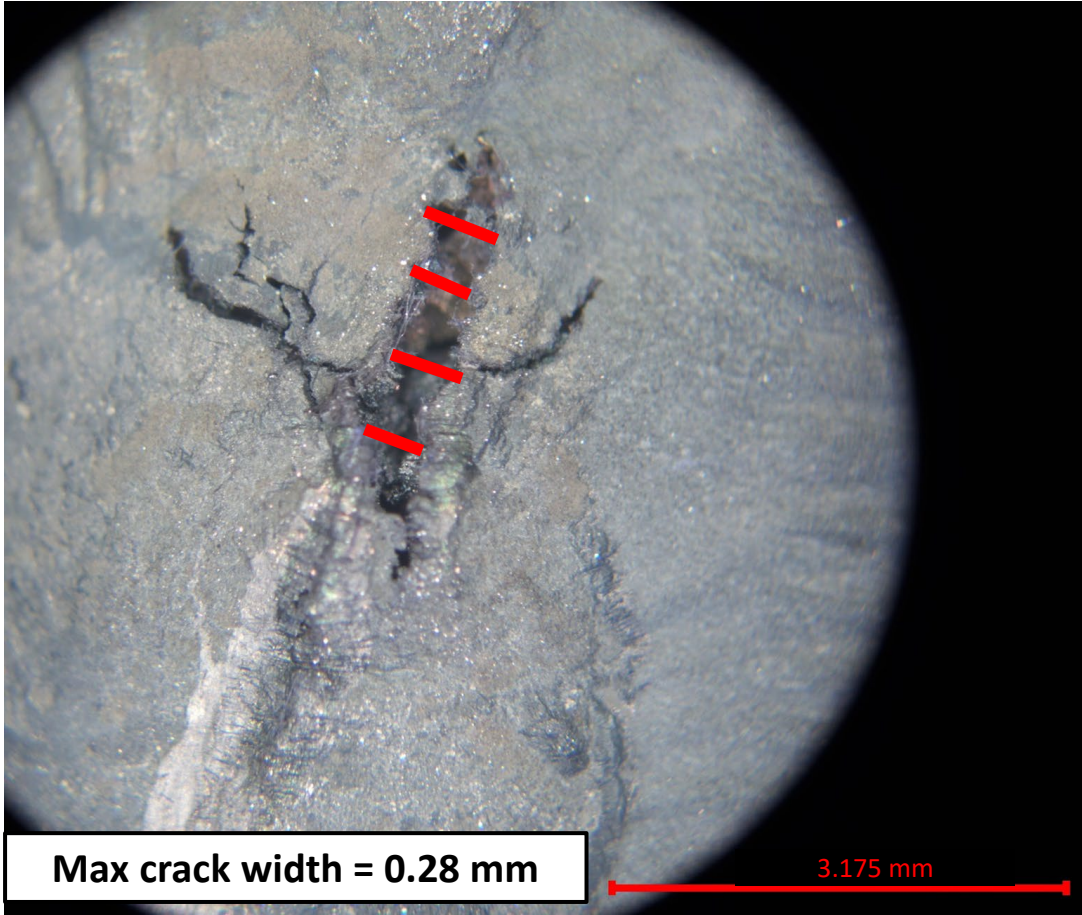


Weldability numerically assessed by maximum crack length, total crack length, and maximum crack width

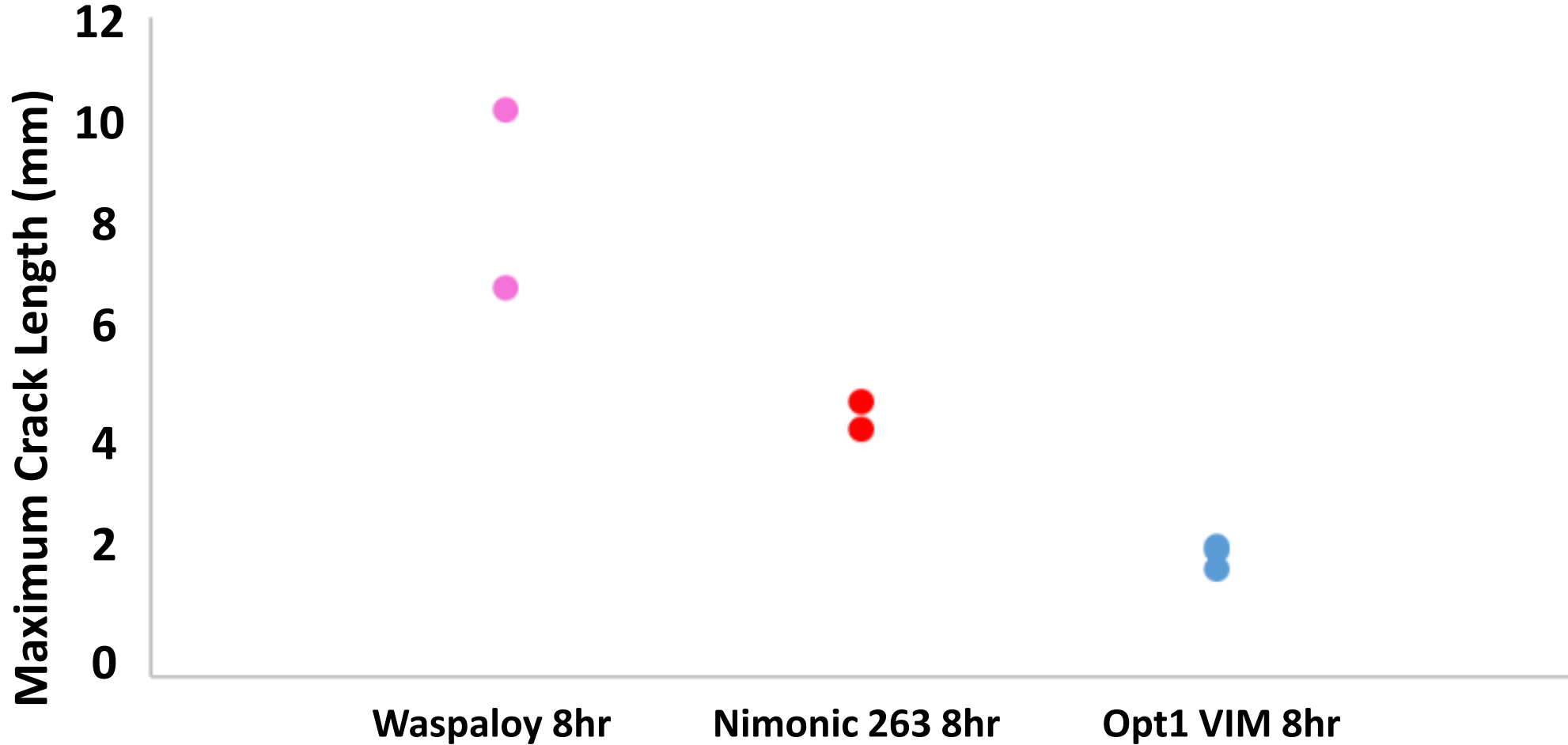
Crack Length Measurements on Nimonic 263



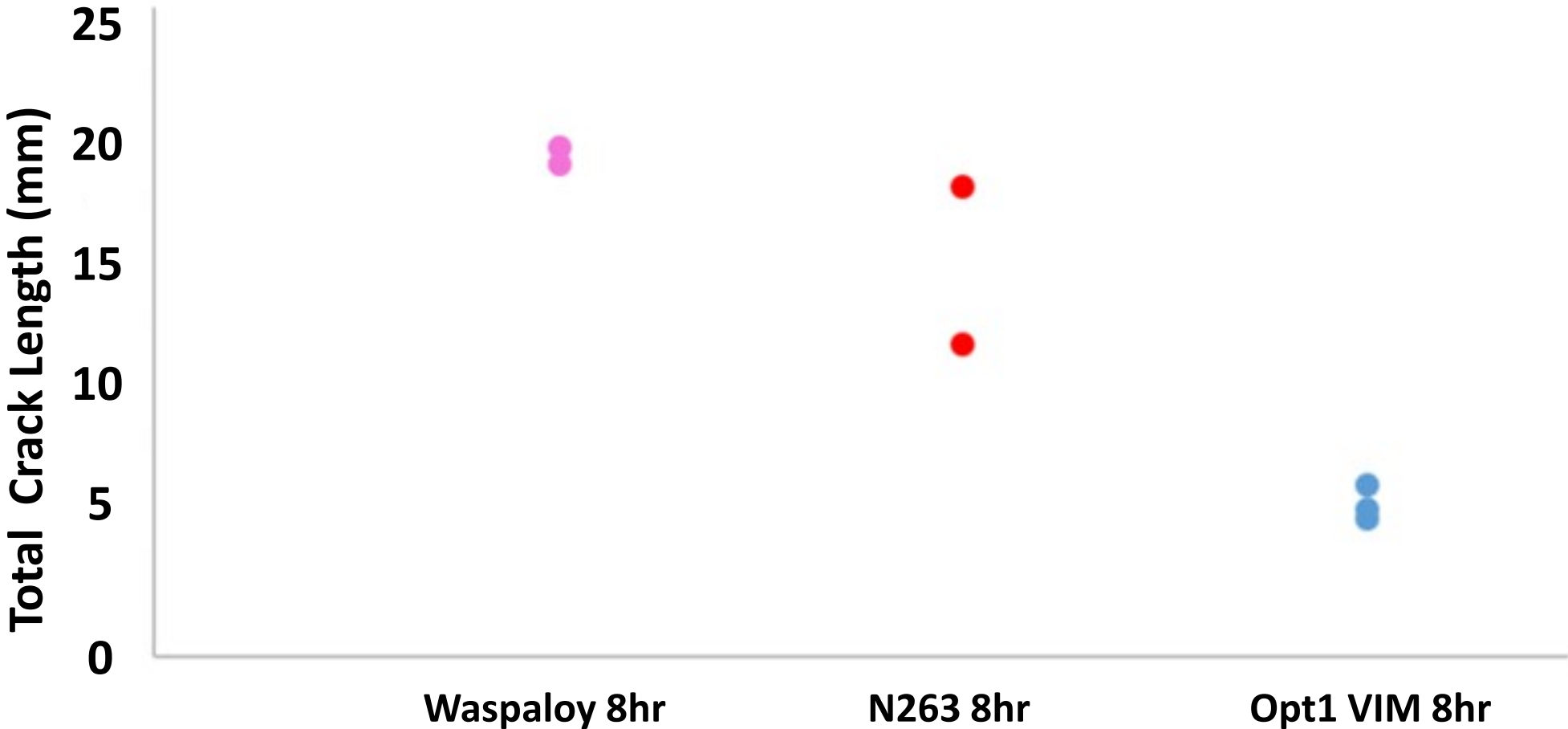
Crack Width Measurements on Nimonic 263



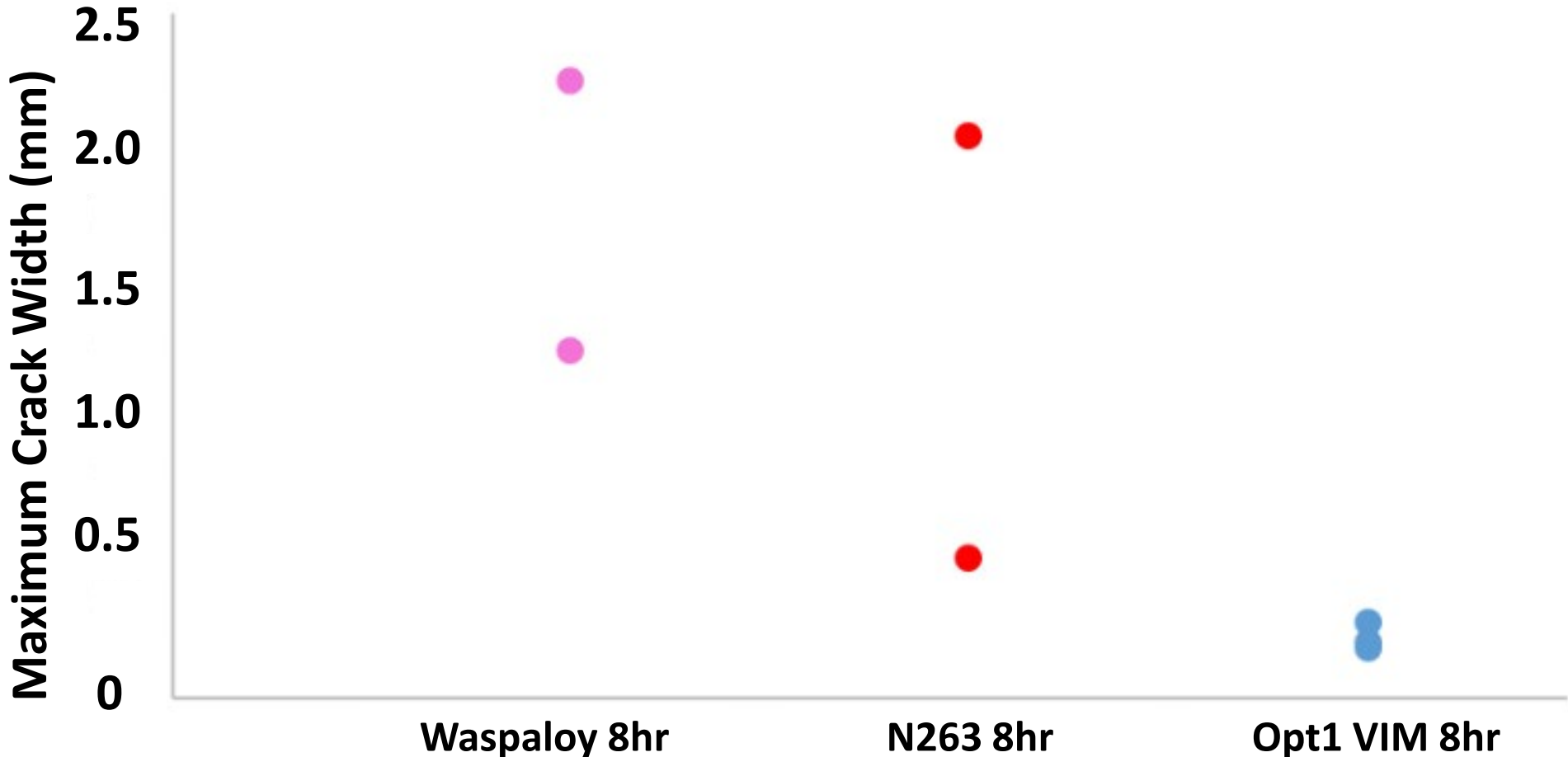
Optimized composition weldability outperforms Waspaloy and N263



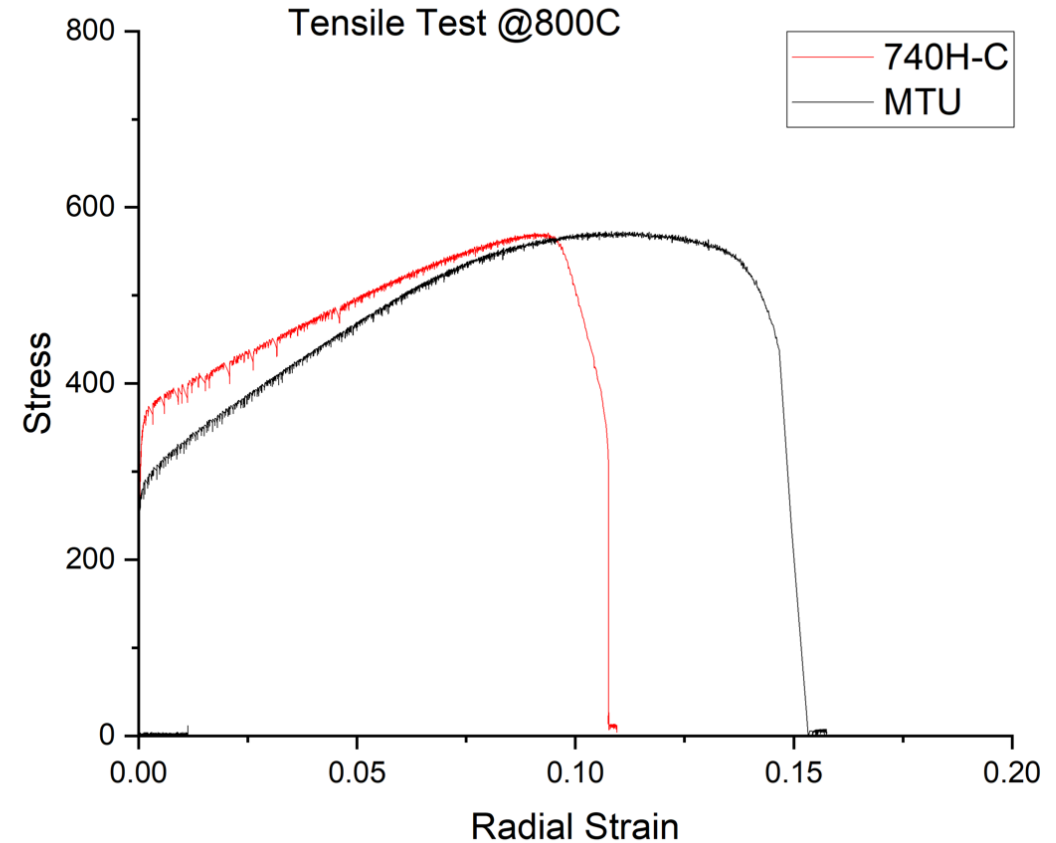
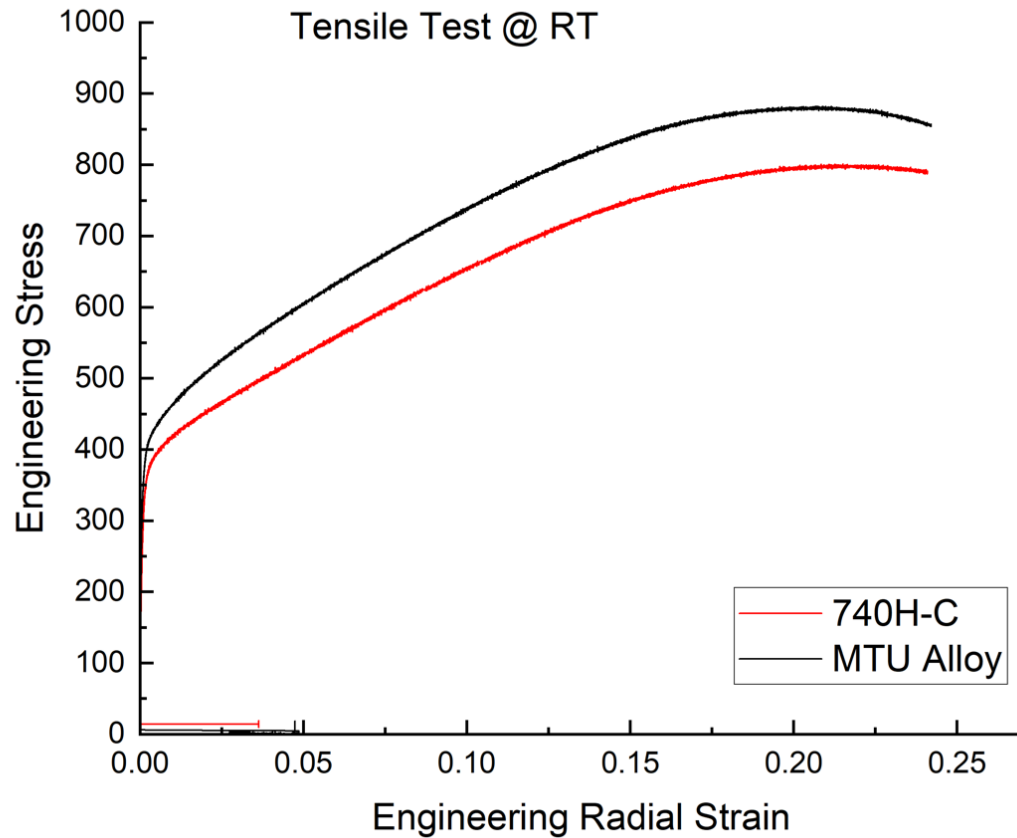
Optimized composition weldability outperforms Waspaloy and N263



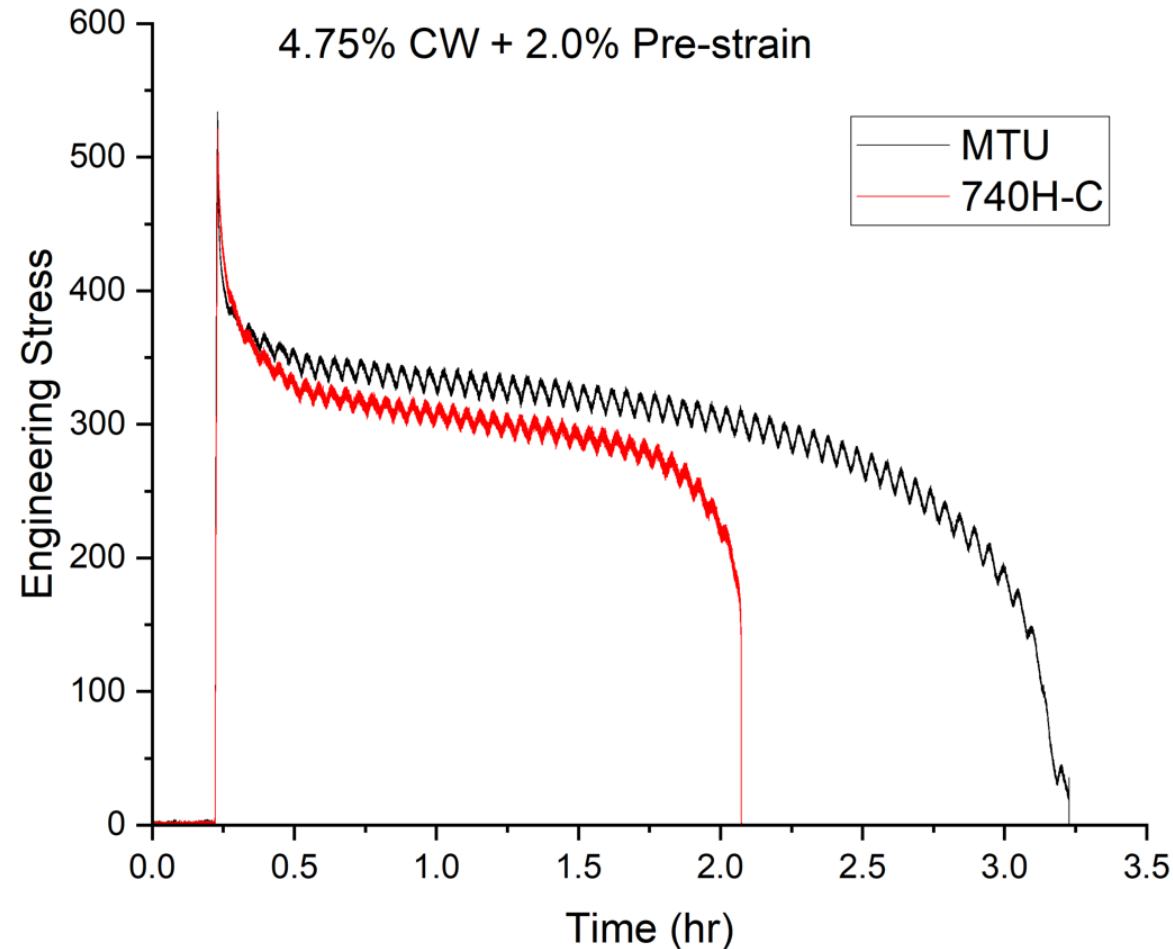
Optimized composition weldability outperforms Waspaloy and N263



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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