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Improving Mechanical Properties in Heavy Section Austenitic Steel Castings

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Innovative Casting Technologies (ICT)

AMC Technology Review

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LEHIGH UNIVERSITY

SFSA

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Overview

Duration

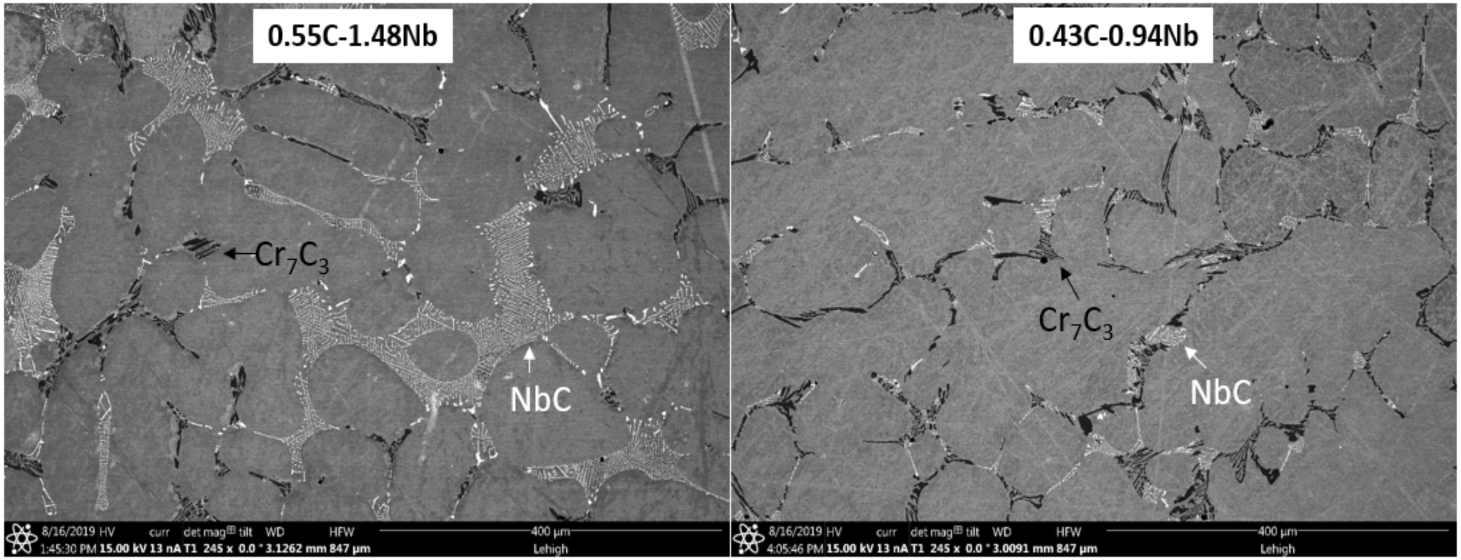
1	2	3	4	5

- HP-Nb (25Cr-35Ni-Nb) alloys are used in high temperature (>850°C) corrosive environments in the as-cast condition
- High carbon content (>0.35wt.%) to form carbides for improved creep strength[2,3]
- Tensile properties can be difficult to achieve
- Cracks have been reported to form during welding and riser removal

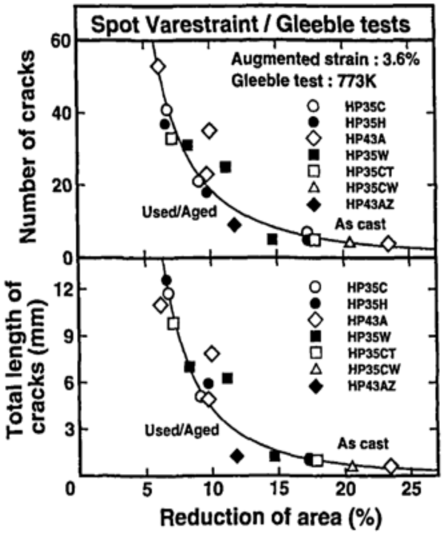
ASTM Specification	Concentration (wt. %) - values are maximum unless otherwise indicated						
	C	Mn	Si	Cr	Ni	Nb	Fe
A608: HP-Nb	0.38-0.45	0.5-1.5	0.5-1.5	24-27	34-37	0.5-1.5	BAL
A608: HP-Nb-Si	0.38-0.45	0.5-1.5	0.5-2.5	24-27	34-37	0.5-1.5	BAL
A297: HP	0.35-0.75	2	2.5	24-28	33-37	-	BAL

HP-Nb Petroleum Refinement Tubes[1]

Backscattered Electron Images of As-Cast HP-Nb alloys within ASTM Specifications



Weldability of HP-Nb[4]



Needs: Understand the relationship between composition, microstructure and tensile properties in high carbon, austenitic castings (and influence of aging)

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Overview (cont.)

- **Needs:** A complete understanding of how composition and aging affects the microstructure (carbide types and amounts) and resultant tensile properties of High Carbon Austenitic castings

- **Benefits:**
  - **Foundries:** Improved quality and performance - foundries will be able to optimize casting composition in order to meet tensile properties and improve weldability
  - **DoD / DLA:**
    - Higher performing and stronger steel castings
    - Scrap reduction, leading to reduced production lead times

- **Progress:**
  - Detailed correlations have been developed between alloy composition, microstructure and tensile properties.
  - Property diagrams have been developed as a guide to foundries.
  - Additional work in progress to establish the influence of aging during service.

- **Transition:** SFSA Webinars, conference publications (T&O), and reports/publications.

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Objective/Approach

Objective

Determine the influence of composition on the microstructure (carbide type/amount) and tensile properties in order to recommend compositions predicted to meet minimum tensile requirements.

Approach

Influence of Microstructure on Tensile Properties

- Tensile fracture mechanism
- Quantitative Image Analysis (QIA)

Influence of Composition on Solidification Behavior

- Experimental γ(Fe/Ni)-C-Cr-Nb Liquidus Projection

Influence of Solidification Behavior on Microstructure

- Thermo-Calc and Linear Regression Modeling

Influence of Composition on Tensile Properties

- Property diagrams/recommended composition ranges

	Alloy Matrix (wt. %)							
Sample name	C	Cr	Ni	Mn	Si	Mo	Nb	Fe
SC:1-10	**0.32 - 0.57**	**23.0 - 25.3**	**32.5 - 35.1**	**0.83 - 0.96**	**1.25 - 1.48**	**0.03 - 0.06**	**0.45 - 1.91**	**BAL**
SC-1	0.32	24.5	34.6	0.94	1.47	0.06	0.45	BAL
SC-2	0.57	25.1	34.6	0.94	1.25	0.05	0.48	BAL
SC-3	0.35	23.9	33.8	0.91	1.27	0.03	1.09	BAL
SC-4	0.52	24.4	33.9	0.96	1.25	0.03	1.39	BAL
SC-5	0.34	24.9	34.5	0.89	1.31	0.04	1.91	BAL
SC-6	0.55	24.8	34.9	0.92	1.43	0.04	1.83	BAL
SC-7	0.43	25.3	35.1	0.83	1.48	0.04	1.21	BAL
SC-8	0.45	23.0	32.6	0.83	1.29	0.04	1.20	BAL
SC-9	0.47	23.0	32.5	0.87	1.28	0.04	1.20	BAL
SC-10	0.45	23.7	33.2	0.95	1.31	0.04	0.63	BAL
CC-1	0.40	24.6	33.2	0.84	1.93	0.08	1.28	BAL
CC-2	0.42	25.4	35.7	0.95	2.00	0.30	1.11	BAL

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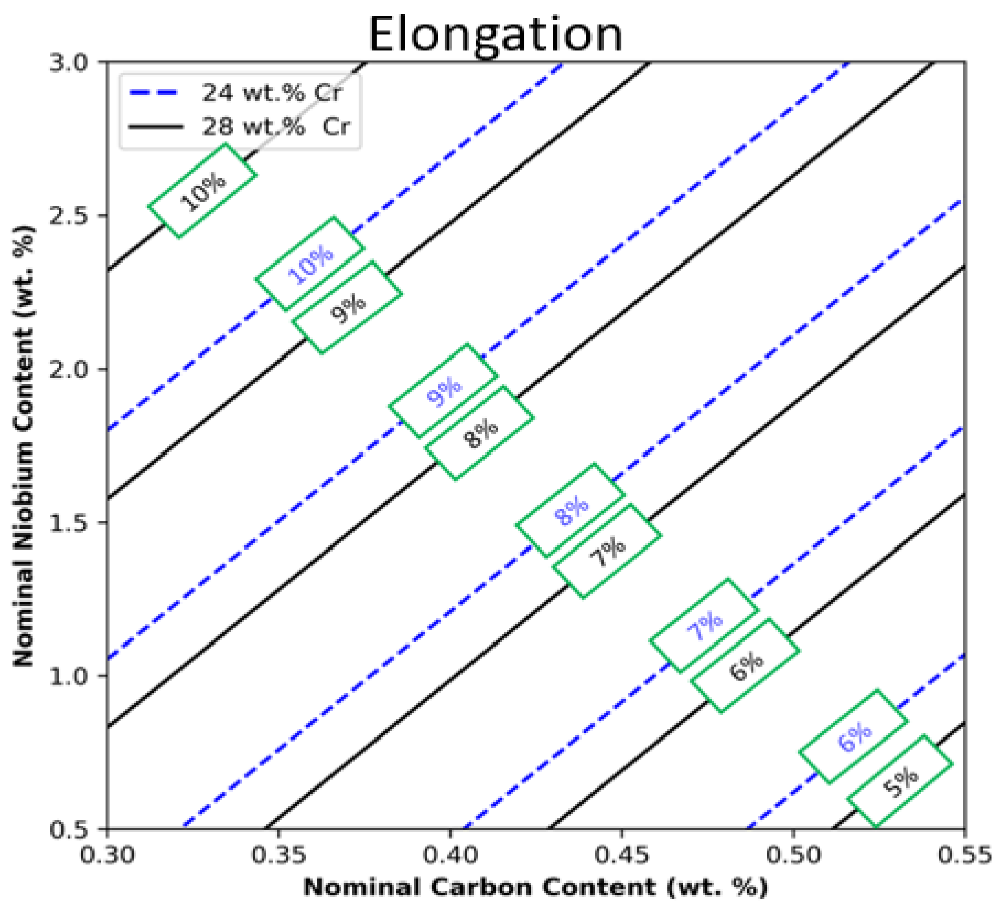
Example – Property diagram showing how composition effects ductility



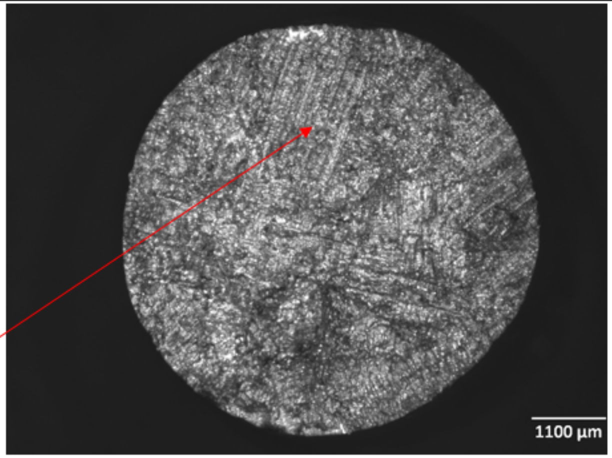
"Heat resistant cast alloys are used extensively for a broad range of industrial high-temperature applications. These materials were initially developed over decades of trial and error alloying methods. On this project, we are able to rapidly optimize alloy compositions using computational modeling to predict composition-structure-property relationships."
Roman Pankiw, Vice President Engineering and Sales, Duraloy Technologies Inc.

Diagram can be used to optimize ductility through composition control

Technical Progress

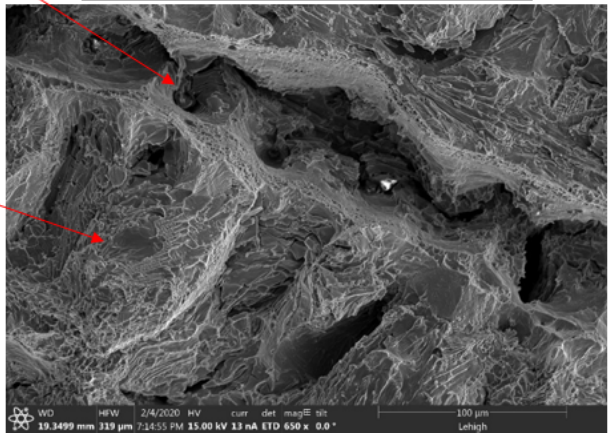
Tensile Properties of HP-Nb Alloys

Stereo micrograph of Tensile Fracture surface



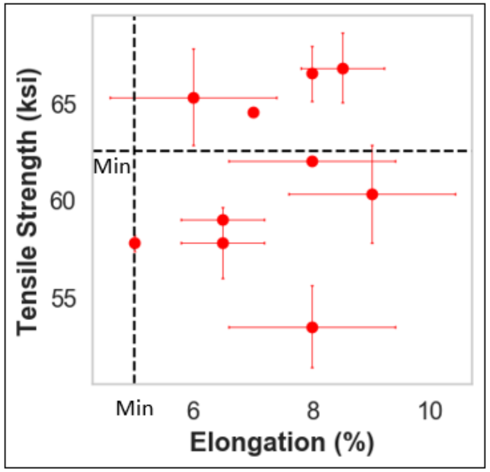
Dendrites

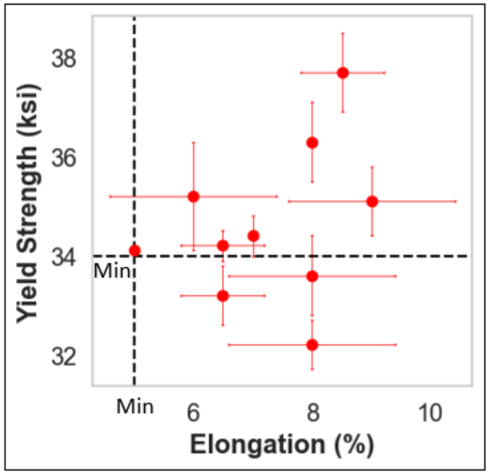
SEM Image of Fracture Surface



Cleavage

Tensile Results



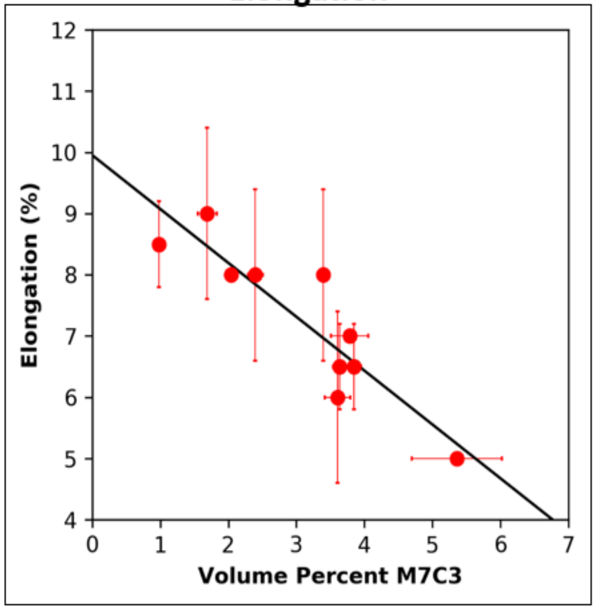


- Room temperature tensile tests were conducted in duplicate according to ASTM E8[8]
- Many samples do not meet the tensile and yield strength requirements
- Samples tested barely meet the required ductility
- Samples evaluated exhibited cleavage fracture along dendrite boundaries

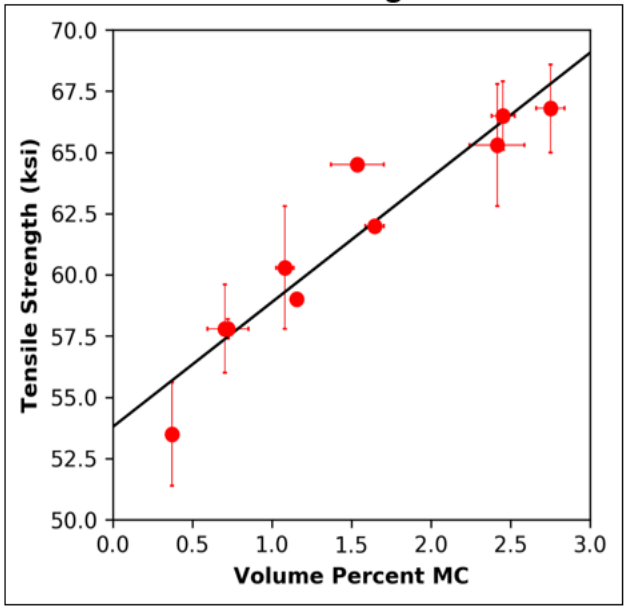
Technical Progress

Influence of Microstructure on Tensile Properties

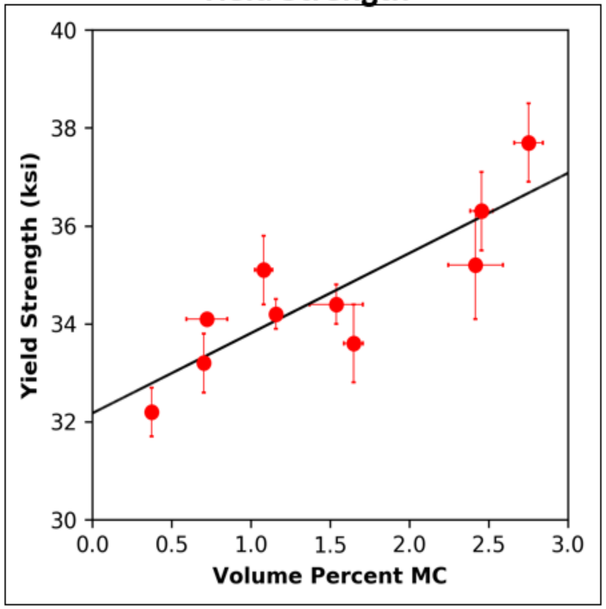
Elongation



Tensile Strength



Yield Strength



$$\text{Elongation (\%)} = 10.5 - 1.02 * F_{M_7C_3}$$

$$\text{Tensile Strength (ksi)} = 53.8 + 5.09 * F_{MC}$$

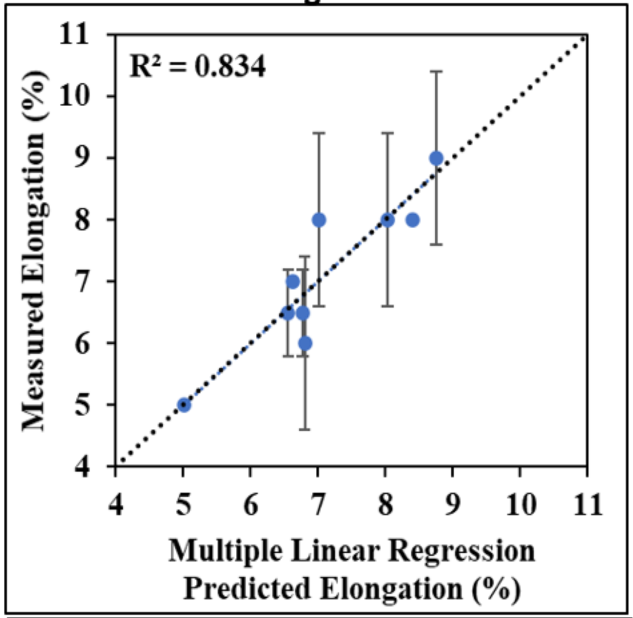
$$\text{Yield Strength (ksi)} = 32.2 + 1.64 * F_{MC}$$

- Increases in the amount of M_7C_3 result in a detriment to elongation
- Increases in the amount of MC show no detriment to elongation but increase the yield and tensile strength
    - Lamellar morphology provides additional barriers to dislocation motion/higher hardness
- Linear regression provides empirical relationships between the microstructure and mechanical properties

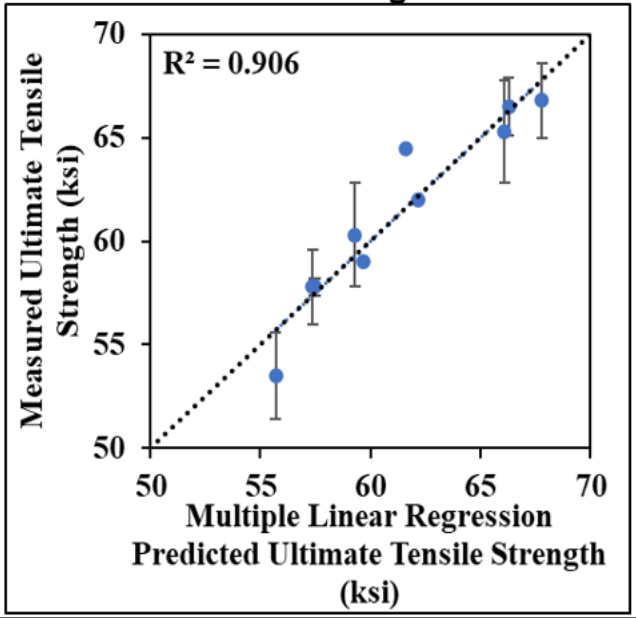
Technical Progress

Influence of Microstructure on Tensile Properties

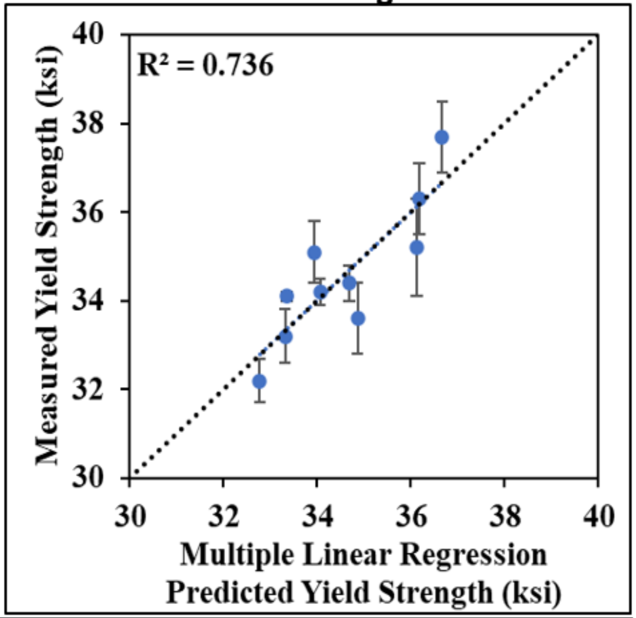
Elongation



Tensile Strength



Yield Strength



Elongation (%) $= 10.5 - 1.02 * F_{M_7C_3}$	Tensile Strength (ksi) $= 53.8 + 5.09 * F_{MC}$	Yield Strength (ksi) $= 32.2 + 1.64 * F_{MC}$

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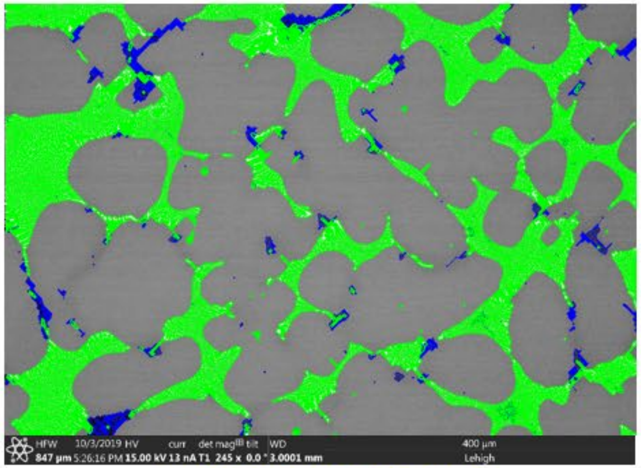
- Linear regression provides empirical relationships between the microstructure and mechanical properties

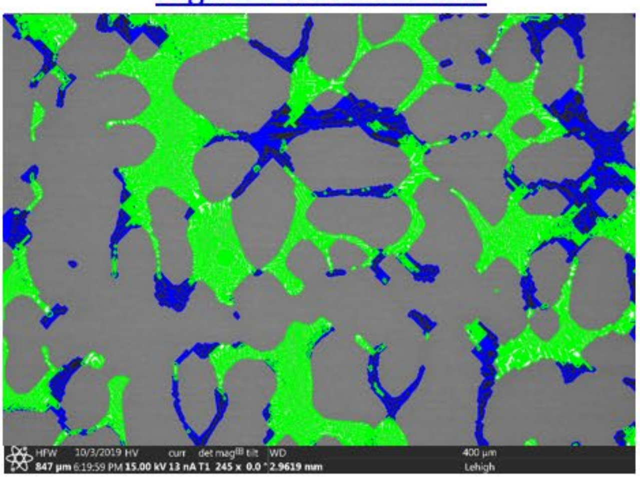
Technical Progress

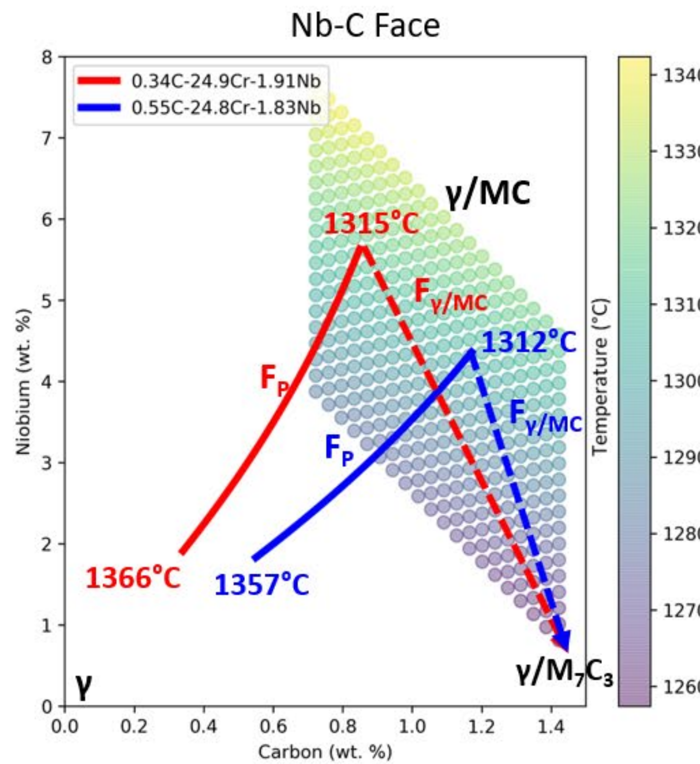
Influence of Carbon

Low C : **0.34**C-1.91Nb



High C : **0.55**C-1.83Nb





Alloy ID	Fraction Primary Austenite (F_P) (vol.%)	Fraction Chromium Carbide (vol.%)	Fraction Niobium Carbide (vol.%)
0.34C-24.9Cr-1.91Nb	**76.6 ± 1.75**	**0.98 ± 0.75**	2.75 ± 0.64
0.55C-24.8Cr-1.83Nb	**70.3 ± 3.18**	**3.61 ± 1.11**	2.42 ± 0.66

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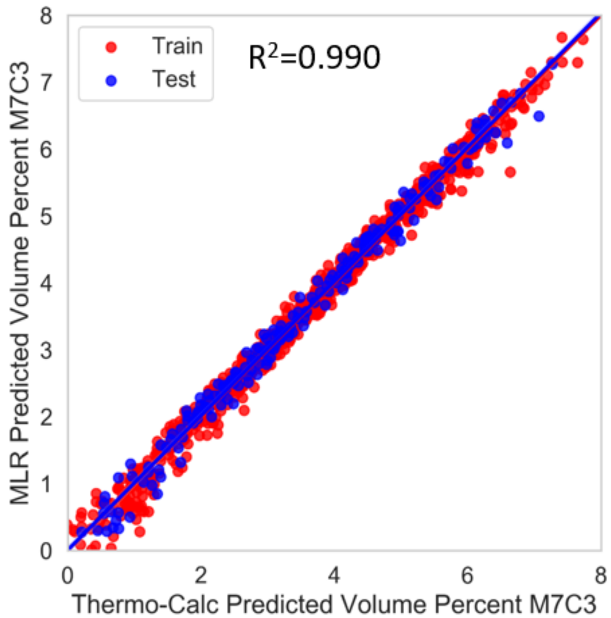
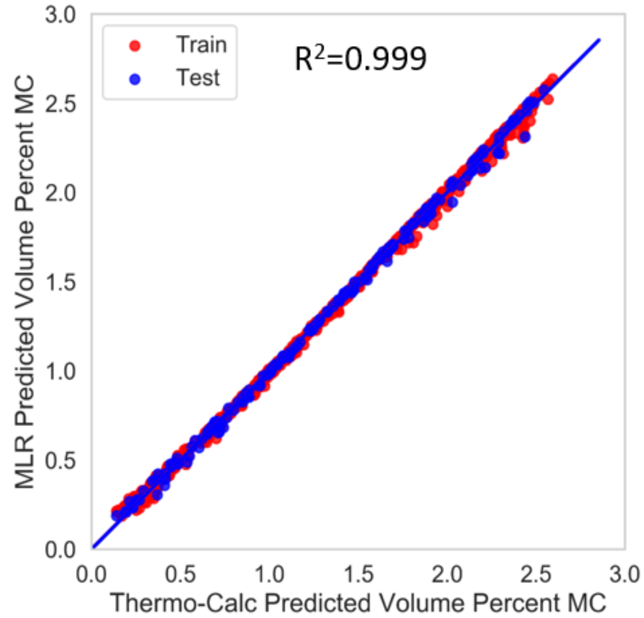
Technical Progress

TC-Python Scheil Solidification Modeling





$$F_{M_7C_3} = -0.042\text{Ni} + 0.147\text{Cr} - 1.26\text{Nb} + 10.1\text{C} + 0.465\text{Si} - 3.00$$

$$F_{MC} = -0.004\text{Ni} - 0.0087\text{Cr} + 1.07\text{Nb} + 0.24\text{C} + 0.082\text{Si} - 0.023$$

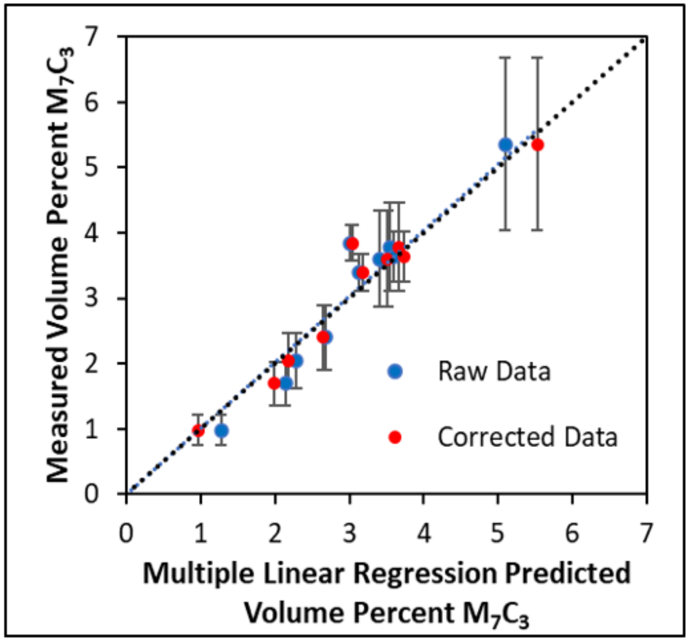
Thermo-Calc Scheil solidification modeling of 1000 alloys:

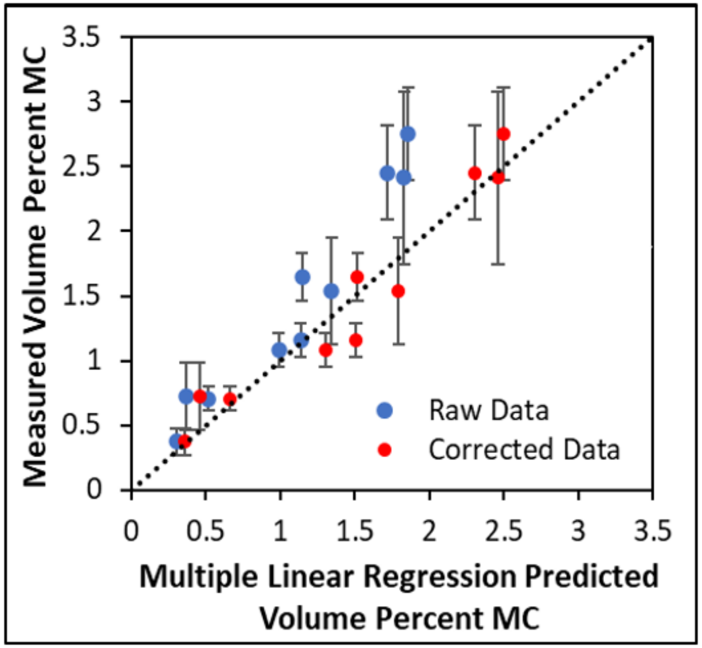
- Input: Composition (randomized for each element within the ASTM standards)
- Output: Phase fractions of each constituent

- Results were fit to a multiple linear regression model
  - Regression analysis provides an empirical equation relating composition to the microstructure
  - Statistically significant due to the large dataset utilized and results include the effect of solute partitioning

Technical Progress

Influence of Solidification on Microstructure





$$F_{M_7C_3} = -0.042Ni + 0.147Cr - 1.26Nb + 10.1C + 0.465Si - 3.00$$

$$F_{M_7C_3} = 1.21F_{M_7C_3} - 0.57$$

$$F_{M_7C_3} = -0.049\mathrm{Ni} + 0.172\mathrm{Cr} - 1.32\mathrm{Nb} + 11.9\mathrm{C} + 0.544\mathrm{Si} - 3.85$$

$$F_{MC} = -0.004Ni - 0.0087Cr + 1.07Nb + 0.24C + 0.082Si - 0.023$$

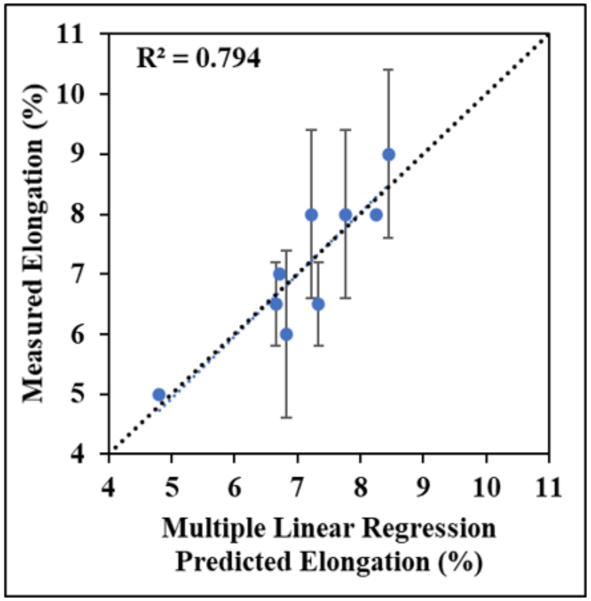
$$F_{MC} = 1.37F_{MC} - 0.05$$

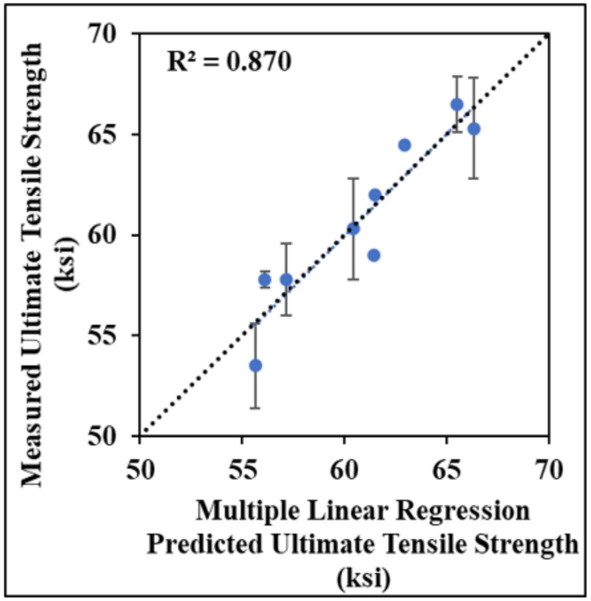
$$F_{MC} = -0.006Ni - 0.012Cr + 1.47Nb + 0.33C + 0.11Si - 0.082$$

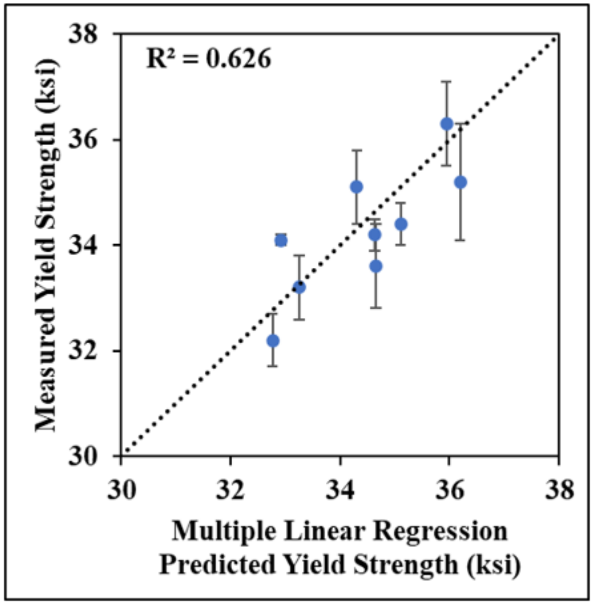
- Multiple linear regression results show small disagreement with measured results for the volume percent of M_7C_3 and MC carbides.
- Bias correction factor is used to correct for errors in the simulated results.[23,24]

Technical Progress

Influence of Composition on Tensile Properties







$$\text{Elongation (\%)} = 0.05Ni - 0.175Cr + 1.34Nb - 12.1C - 0.555Si + 14.4$$

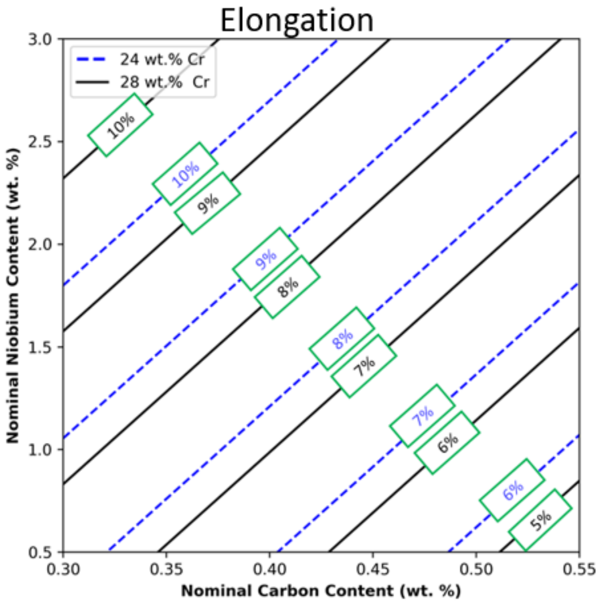
$$\text{Tensile Strength (ksi)} = -0.029Ni - 0.061Cr + 7.49Nb + 1.66C + 0.58Si + 54.2$$

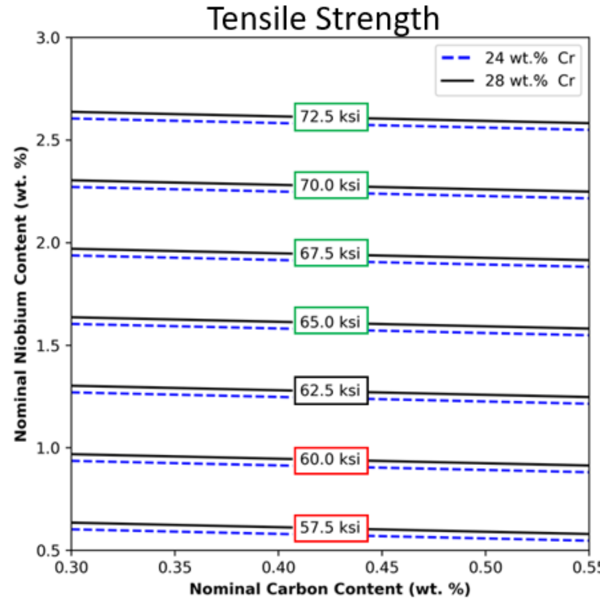
$$\text{Yield Strength (ksi)} = -0.009Ni - 0.019Cr + 2.41Nb + 0.534C + 0.185Si + 32.3$$

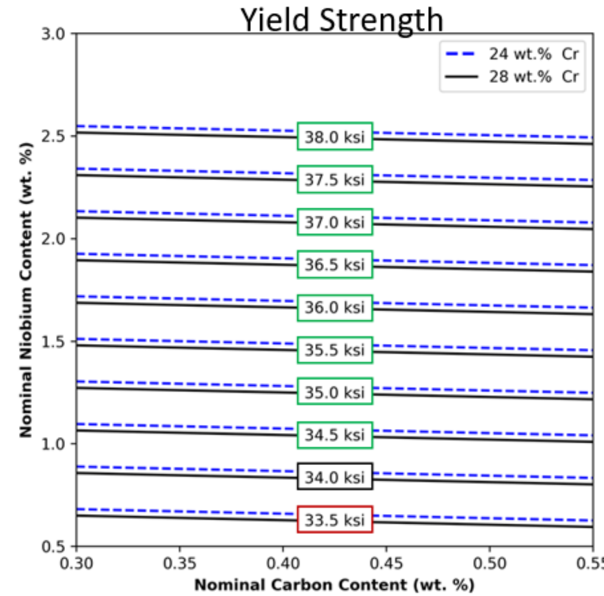
- The regression equations can be combined to determine the empirical relationships between the composition and the tensile properties
  - Positive coefficient is beneficial to the property, negative coefficients are detrimental
- Results are valid for the composition ranges evaluated and for the solidification conditions of the static castings
- Does not consider the mechanistic effects (Hall-Petch, solid solution strengthening, etc.)
- Provides insight into the quantitative relationships between the composition and ambient temperature tensile properties

Technical Progress

Property Diagrams of HP-Nb Alloys







$$\text{Elongation (\%)} = 0.05\text{Ni} - 0.175\text{Cr} + 1.34\text{Nb} - 12.09\text{C} - 0.555\text{Si} + 14.4$$

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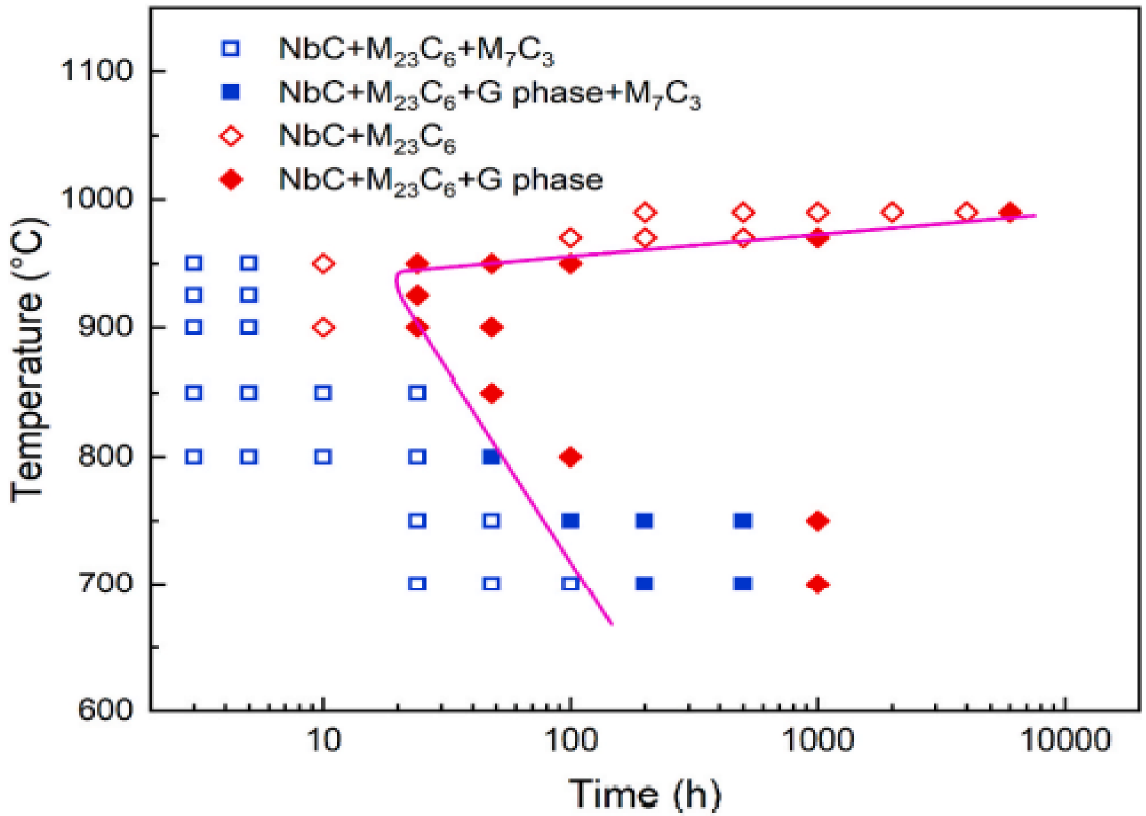
- Regression equations are used to plot the influence of niobium, carbon and chromium with other alloying additions constant
  - Green outline exceeds the minimum requirement, black is the minimum value, red is below the minimum
- Increases in carbon concentration and chromium concentration, reduce the ductility with minimal benefit to tensile or yield strength
- Increases in niobium concentration increases all tensile properties
- All tensile properties are met with a nominal niobium concentration of 1.3wt. %, independent of chromium and carbon additions

Added Objective – Influence of Aging on Properties



TTT diagram of HP40NB alloy determined from X-ray diffraction data by *Fuyang et. al.* [2]

Phase transformations during aging

- M_7C_3 → $M_{23}C_6$ and MC → G-phase ($Ni_{16}Nb_6Si_7$)

How do these changes effect properties ?

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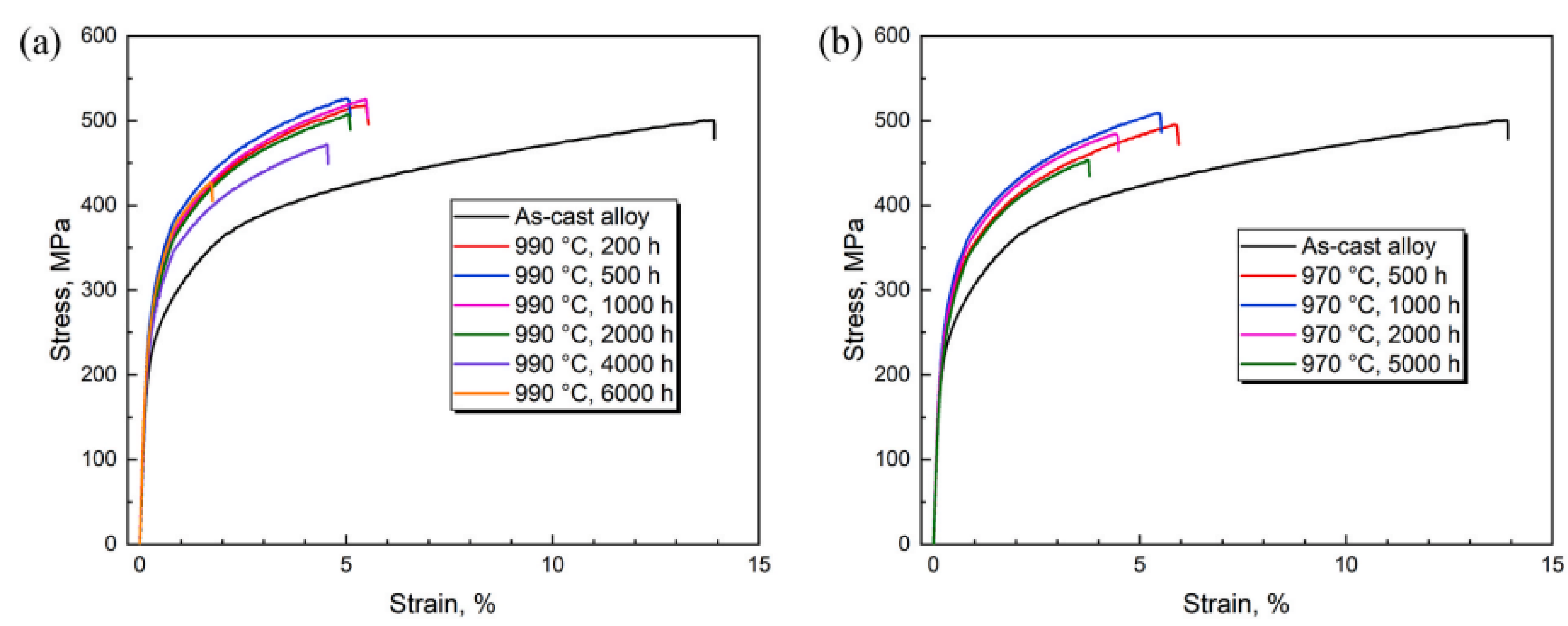
Tensile Properties After Aging



Tensile stress strain plots of HP40NB alloy after aging at (a) 990°C and (b) 970°C from *Fuyang et. al.* [1]

- Ultimate Tensile strength and yield strength increase initially then decrease as aging time increases
- Ductility decreases with aging time
- Influence of alloy composition ??

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Added Objective – Determine influence of composition on properties after aging

Alloy Compositions

	Alloy Matrix (wt. %)																	
Sample ID	**C**	**Cr**	**Ni**	**Mn**	**Si**	**Mo**	**Nb**	**W**	**Ti**	**Al**	**Co**	**Cu**	**N**	**Zr**	**V**	**P**	**S**	**Fe**
SC-A	0.47	23	32.5	0.87	1.28	0.04	1.195	-	-	-	-	0.07	-	-	-	0.015	0.0105	BAL
SC-B	0.45	25.1	34.7	0.91	2.48	0.06	1.34	0.09	0.01	0.04	0.07	0.09	-	-	0.03	0.022	0.009	BAL
SC-C	0.45	24.7	34.4	0.98	1.27	0.04	1.27	0.11	0.12	0.01	0.06	0.08	-	-	0.04	0.019	0.01	BAL
CC-A	0.45	26.7	34.6	0.83	1.5	0.084	1.036	-	0.077	-	-	-	-	-	-	-	-	BAL
CC-B	0.44	25.5	35.4	0.83	2	0.23	1.12	0.1	0.04	0.01	0.0779	0.054	0.05	0.12	0.036	-	-	BAL
CC-C	0.4	24.6	33.2	0.84	1.93	0.077	1.282	-	-	0.003	-	-	-	-	-	-	-	BAL
CC-D	0.44	23.63	34.19	0.91	0.77	0.48	0.38	0.14	0.07	-	-	-	-	-	-	-	-	BAL

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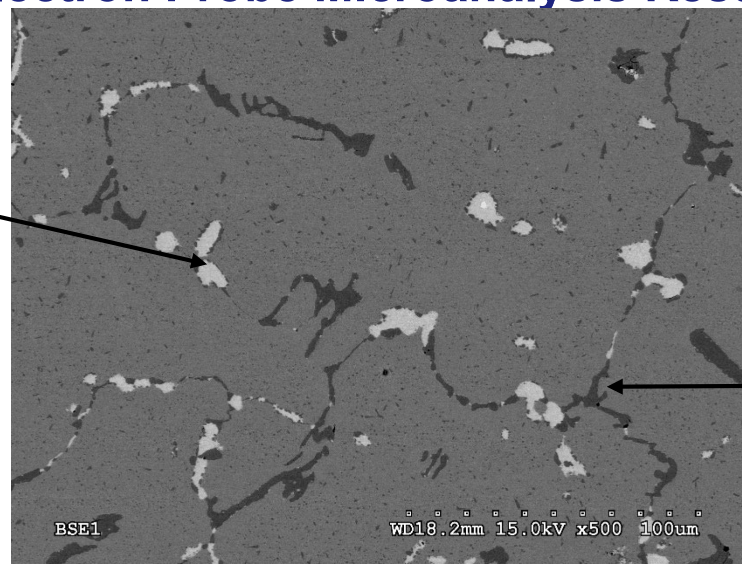
Characterization of Aged Samples

SC-B
Electron Probe Microanalysis Results

1000 hour age at 900 °C

G-Phase



M_7C_3

At. %	Si	Cr	Mn	Fe	Ni	Nb	Ti	C	Suspected Phase
Light Phase	22.75±0.29	1.98±0.17	0.13±0.06	4.82±0.12	49.72±0.86	20.60±0.98	0	0	**G-Phase**
Dark Phase	0.00±0.01	64.18±1.35	0.30±0.07	6.70±0.23	2.59±0.42	0.06±0.02	0	26.17±1.51	**M_7C_3**

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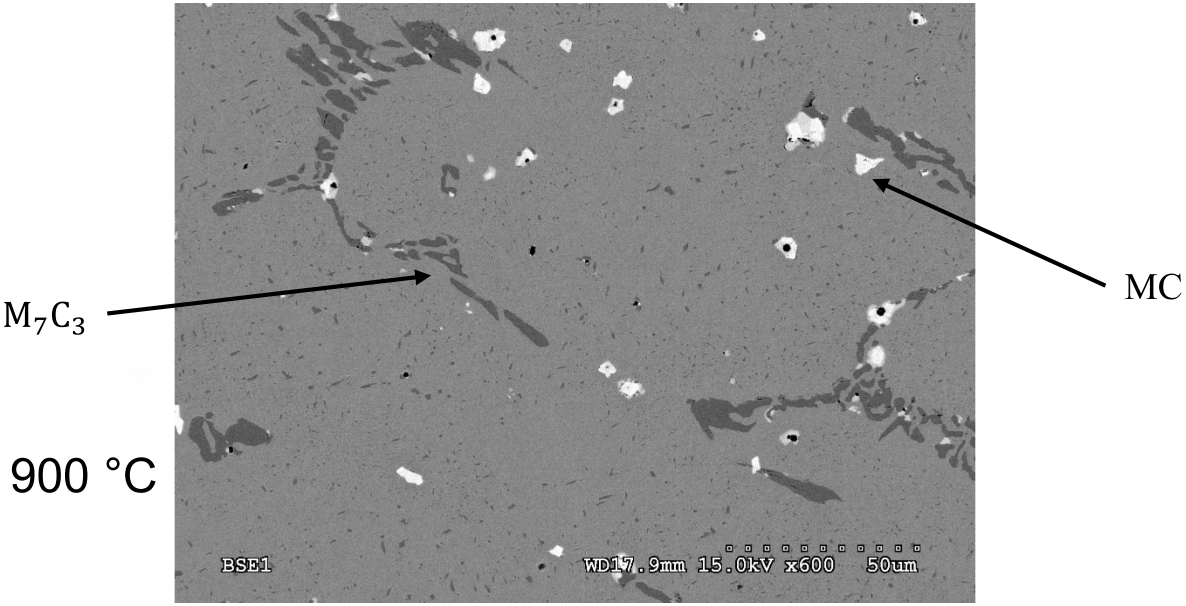
Characterization of Aged Samples

SC-C
Electron Probe Microanalysis Results

1000 hour age at 900 °C



At.%	Si	Cr	Mn	Fe	Ni	Nb	Ti	C	Suspected Phase
Light Phase	0	1.48±0.36	0	0.79±0.09	0.84±0.09	53.06±2.45	6.36±3.10	37.47±3.46	MC
Dark Phase	0	60.03±0.93	0.31±0.04	6.5±0.35	2.35±0.45	0.08±0.02	0	30.72±1.02	M_7C_3

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Conclusions

- Tensile fracture initiates with microcracking of M_7C_3 carbide and propagates along continuous M_7C_3 carbide networks, impeded by MC carbides.
- M_7C_3 carbides are detrimental to ductility with minimal benefit to tensile and yield strength.
- MC carbides are beneficial to yield and tensile strength.
- A novel pseudo-quaternary liquidus projection was constructed and validated using experimental data.
- Increases in carbon concentration result in an increase in the amount of M_7C_3 carbide and therefore decrease in ductility
- Increases in niobium concentration result in the preferential formation of MC carbides, reducing the amount of M_7C_3 carbides.
- Aging and testing of alloys in progress
- Detailed correlations provided between composition, microstructure, and tensile properties.

Completion and Transition Plans

- Original objectives completed ahead of schedule
- Additional tests will be conducted on aged samples to determine the effect of aging on mechanical properties
- A draft final report will be provided to ATI by 10/29/22
- Results have been (and will continue to be) disseminated via SFSA Webinars, conference publications (T&O, ASMI), and reports/publications
  - Webinar foundry participants: Acerlan, Ashland, Bradken-London, Columbia, Duraloy, Fimex, Fisher, Funvesa, Harrison, Howell, Magotteaux, Mayran, ME Global, Metaltek-WC, Midwest, Monett, Northern Stainless, RAMSA, Regal Cast, Southern Alloy, Southern Cast, Waukesha
  - Project partners: UAB, MetalTek, Duraloy, Fisher

Leveraging

- Thermocalc thermodynamic/solidification simulation software used in this project is supported by the National Science Foundation Manufacturing and Materials Joining Innovation Center (Ma^2JIC - a consortium of 6 universities and 52 companies)
- The simulation techniques used for this project were developed on a previous SFSA-DID project.
- UAB – provided the large matrix of experimental cast alloys
- Commercial alloys received from MetalTek and Duraloy
- Valuable input of project direction received from multiple industry partners through SFSA webinars
- Techniques developed in this project are currently being applied to Monel alloys under the DID program

Leveraging

DoD Supported Students and Their Current Positions

Jeff Farren – Carderock Naval Surface Warfare Center

Dan Bechetti – Carderock Naval Surface Warfare Center

Brett Leister – Carderock Naval Surface Warfare Center

Andrew Stockdale – Bettis (Navy Nuclear Propulsion Laboratory)

Erin Barrack – Sandia National Laboratory

Robert Hamlin – KAPL (Navy Nuclear Propulsion Laboratory)

Sean Orzolek – Carderock Naval Surface Warfare Center

AMERICAN METALCASTING CONSORTIUM

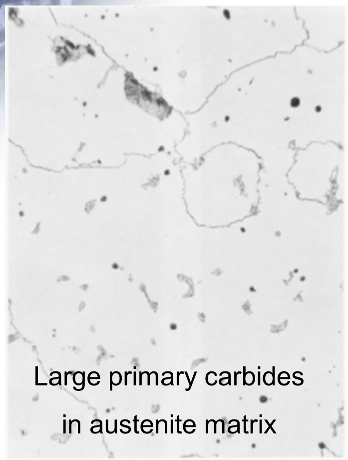
Project Metrics

Description	Baseline	Threshold	Goal	How Measured	Target Date	Progress	How Demonstrated
Establish the influence of composition on carbides and tensile properties in HP cast alloys	HP castings are susceptible to low ductility and cracking during welding	Guidelines on composition for improved tensile properties	Meet ASTM specification requirements and eliminate unexpected cracking	Tensile Testing	March 2021	100%	Production of trial heat with compositions to show improved properties
Effect of section size on the room temperature ductility and strength in HH Type II casting alloys	HH alloys have heats with low room temperature strength and ductility	Identification of section size limitations (and possible comp) for specified properties	Process and/or section size guidance for conformance to specification property requirements	Tensile strength/ elongation ASTM	Jan 2023	85%	Production of test material that shows the process guidance meets required properties
Identify cracking mechanism in thick section castings	Castings can exhibit cracking in thick sections	Current cracking mechanism not fully established	Identify cracking mechanism in thick section castings	Microstructural characterization	Jan 2023	100%	Preparation and examination castings
Identify compositions resistant to detrimental phase formation during aging	HP castings are susceptible detrimental phase formation during aging	Guidelines on compositions for minimizing degradation in tensile properties after aging	Meet ASTM specification requirements after aging	Tensile Testing	October 2022	50%	Tensile testing of alloys after aging

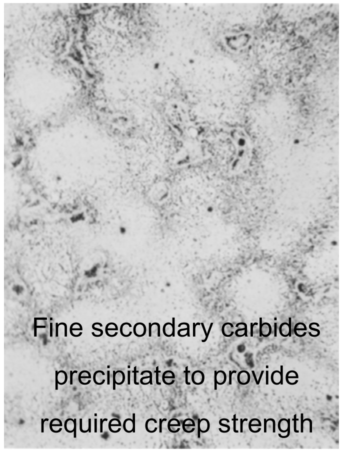
Improving Mechanical Properties in Heavy Section Austenitic Steel Castings

AMERICAN METALCASTING CONSORTIUM

DLA - POC: DLAR.DPR@dla.mil



As Cast



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Problem

Can be difficult to achieve acceptable tensile properties in HH grade castings. HP alloys are susceptible to cracking during welding and riser removal.

Objectives

- Identify the influence of cooling rate and composition on intergranular carbides and associated cracking in HP casting alloys.
- Identify the cause of reduced tensile properties in HH Type II casting alloys.
- Develop guidelines for avoiding cracking and meeting tensile properties.
- **ADDED** - Identify compositions that are resistant to detrimental phase formation during high temperature service.

Benefits to Warfighter

- Improved performance and decreased cost of steel castings
- Strengthened supply chain through advancements in austenitic alloy production

Description of Project:

This project will enhance heat-resistant austenitic steel grade properties to improve performance, reduce the scrap/rework resulting from the elimination of false positive indications, and strengthen the supply chain through the advancement in austenitic alloy production.

Team:

Lehigh University, Steel Founders' Society of America, ATI

LEHIGH UNIVERSITY SFSA ATI ADVANCED TECHNOLOGY INTERNATIONAL

Milestones / Deliverables

•HP Grades: Establish influence of alloy composition and section size on phase balance and tensile properties

•HH Type II Grade: Establish influence of phase balance on tensile properties (possibly establish limits for section size)

•Dissemination of processing guidelines and results to industry via committee meetings, professional conferences, and publications