Investigation of Variable Manganese and Nickel Content on Ductile Iron Castings Utilizing Ionic Liquids Isolated Iron and Bosch Carbon

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About the Presenter

- Blake C. Stewart
  - Graduate Research Assistant
  - Ph.D. candidate
  - B.S. Mechanical Engineering
- Highlights and Interests
  - Steelmaking and cast iron
  - In-situ resource utilization (ISRU)
  - Extraterrestrial manufacturing methods
  - Experience in manufacturing, field engineering, and experimental research

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About the Presenter

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Motivation

- In-situ resource utilization techniques required for long-term habitation on extraterrestrial surfaces[1]
- Various mechanical and structural components needed from resources available in Lunar and Martian environments[2]
- Martian regolith is rich in metallic elements but are found as silicate minerals containing bound metal elements

Artist rendering of humans and habitats on Martian surface[3]

[1] A. Owens, et. al, 2015 [2] Barker, et. al, 1998 [3] NASA JPL, 2019

Overview

- Ductile iron alloys cast with Bosch-sourced carbon (C) and utilizing ionic liquids harvested iron (IL-Fe) composition
  - Four chemistries chosen as combinations of low and high nickel (Ni) and manganese (Mn)
- Produced ingots evaluated to determine effects of additional alloying in Martian environment
  - Dilatometry
  - Characterized microstructure
  - Mechanical properties (hardness)
- Investigation provides viability in using IL-Fe and Bosch C in casting multiple grades of ductile iron with minimal elemental additions

Introduction: Martian Environment

- **Martian regolith contains metallic elements bound in silicate compounds that could be used for tools, components, and infrastructure[4-9]**
- **Martian environment rich in CO_2[10]**

Average Chemical Composition of Martian regolith[4-9]	
SiO_2 (n=40)	48 ± 6
MnO (n=20)	0.3 ± 0.1
Fe_xO_x (n=40)	15 ± 4
Ni (n=11)	0.02 ± 0.01
MgO (n=40)	6 ± 2
Al_2O_3 (n=40)	12 ± 5
CaO (n=40)	8 ± 2
Cr_2O_3 (n=14)	0.2 ± 0.2
	(wt.%) ± st.dev.

[4] A.S. Yen, et. al, 2013
[5] R.V. Morris, et. al, 2015
[6] M.J. Rutherford, et. al, 1999
[7] G. Peters, et. al, 2008
[8] C. Allen, et. al, 1998
[9] C. Allen, et. al, 1997
[10] P. Mahaffy, et. al, 2013

Introduction: Ionic Liquids Iron Harvesting

- ILs currently studied at MSFC to extract metallic elements from regolith and meteorites as well as a life support system[11-14]
- Current production rate: 1-2 g/day
- IL is regenerated after harvesting[15]

$$2HSO_4^- + MO \rightarrow 2SO_4^{2-} + M^{2+} + H_2O$$

$$M^{2+} + 2e^- \rightarrow M \,\|\, 2SO_4^{2-} + H_2 \rightarrow 2HSO_4^- + 2e^-$$

Average Metallic Chemical Composition of IL-Fe (n=3)	
Si	1.40 ± 0.3
Mn	0.47 ± 0.1
Fe	95.4 ± 0.4
Ni	0.14 ± 0.02
MgO	2.27 ± 0.3
Al	0.11 ± 0.1
Ca	0.11 ± 0.1
Co	0.08 ± 0
Na	0.04 ± 0.03
	(wt.%) ± st.dev.

[11] B. R. Brown, et. al, 2017
[12] B. R. Brown, et. al, 2018
[15] E. T. Fox, 2019
[13] L. J. Karr, et. al, 2018
[14] A. Asiaee, et. al, 2020

Introduction: Bosch Carbon

- **Bosch process studied at MSFC as an oxygen (O_2) regeneration system producing a by-product C[16-18]**
- **Bosch C previously studied in alloying for low C steel, gray iron, and ductile iron[19-21]**
- **Current production rate: 8-10 g/hr**

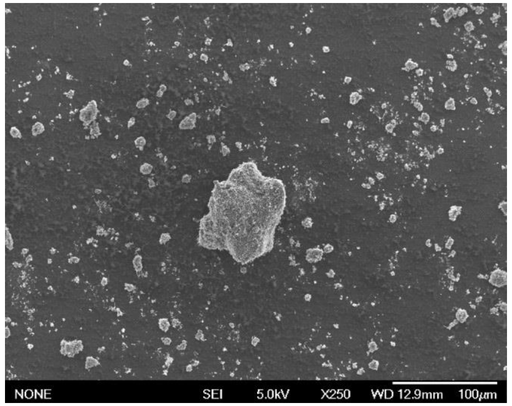
$$CO_2 + H_2 \leftrightarrow H_2O + CO$$

$$CO + H_2 \leftrightarrow H_2O + C(s)$$

$$2CO \leftrightarrow CO_2 + C(s)$$

$$\boldsymbol{CO_2 + H_2 \leftrightarrow 2H_2O + C(s)}$$

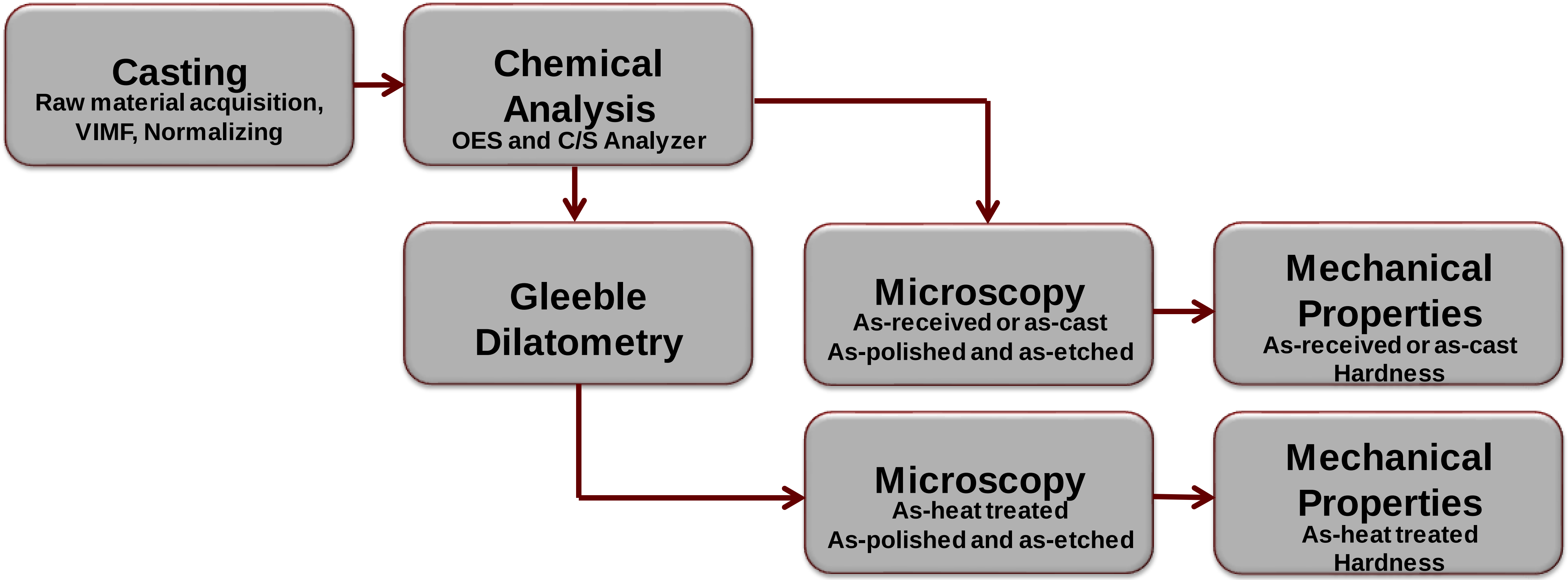
Series-Bosch catalyst test stand[16]



Bosch C morphology[20]

[16] M. B. Abney and J. M. Mansell, 2011
[17] M. B. Abney, et. al, 2013
[18] M. B. Abney, et. al, 2014
[19] B. C. Stewart, 2019
[20] B. C. Stewart, 2021
[21] B. C. Stewart, et. al, 2021

Experimental Evaluations



Chemical Composition

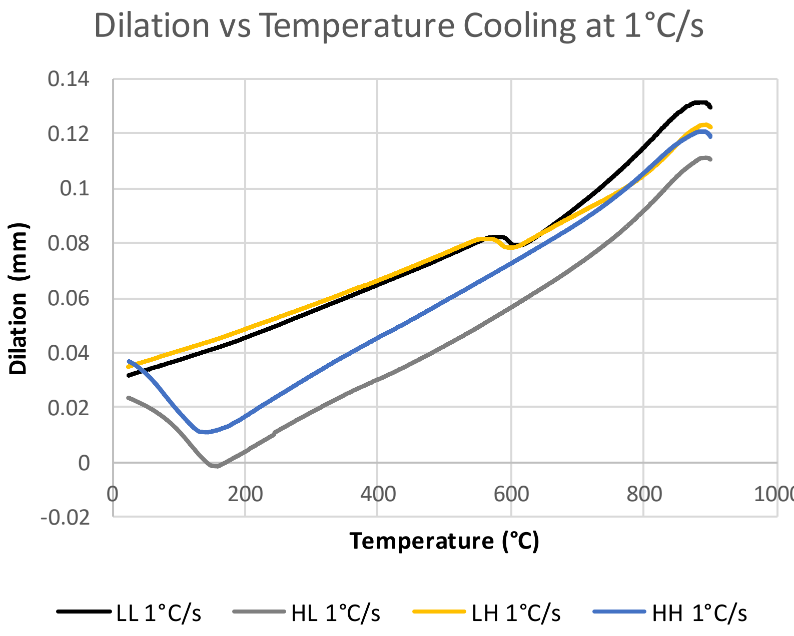
- Composition measured with optical emission spectrometer (OES) w/ C verified with C/S analyzer
- Ni values targeted: Low (L-Ni): 0.14 wt.% and high (H-Ni): 4 wt.%[22]
- Mn values targeted: Low (L-Mn): 0.41 wt.% and high (H-Mn): 1 wt.%[23]

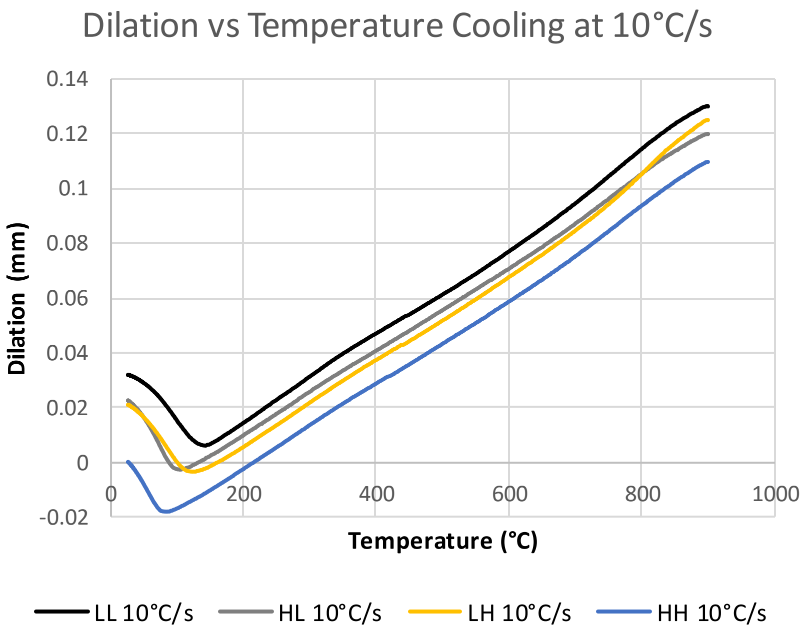
Chemical composition of Cast Ingots (n=10)									
	C	Si	Mn	Ni	Al	Co	Ca	Mg	Fe
L-Ni / L-Mn	3.53^ ± 0.02	1.43 ± 0.02	0.497 ± 0.003	0.150 ± 0.004	0.053 ± 0.002	0.081 ± 0.003	0.004 ± 0.003	0.046 ± 0.004	bal
H-Ni / L-Mn	3.37^ ± 0.05	1.44 ± 0.01	0.51 ± 0.005	4.25 ± 0.02	0.07 ± 0.001	0.084 ± 0.002	0.002 ± 0.0003	0.042 ± 0.003	“
L-Ni / H-Mn	3.59^ ± 0.02	1.36 ± 0.03	1.01 ± 0.01	0.156 ± 0.002	0.056 ± 0.001	0.062 ± 0.002	0.002 ± 0.001	0.044 ± 0.004	“
H-Ni / H-Mn	3.54^ ± 0.04	1.46 ± 0.02	1.04 ± 0.01	4.38 ± 0.02	0.067 ± 0.002	0.088 ± 0.002	0.003 ± 0.002	0.055 ± 0.005	“
^n=3 from C/S analyzer					(wt.%) ± st.dev.				

[20] C. Hsu, 2007
[21] DIS, 2001

Dilatometry

- **6 mm OD x 22 mm L samples heated at 5°C/s to 900°C, held for 30 min, and cooled at prescribed cooling rate[24]**
- **Contact dilatometer used to measure change throughout testing**
- **Cooling rates performed: 1 and 10°C/s**





[22] Samuel and Viswanathan, 2008

Transformation Temperatures

- **Transformation temperatures show similarities with H-Ni and L-Ni in separate “classes”**
- **H-Ni materials readily obtain martensite even at a relatively slow rate**
- **Mn does not seem to drastically affect material performance despite also encouraging austenite stability**

Transformation Temperatures						
°C/s	Mat’l	F_S	F_F,P_S	P_F,B_S	B_F	M_S
1	L-Ni / L-Mn	755	627	563	-	-
	H-Ni / L-Mn	-	-	546	365	162
	L-Ni / H-Mn	817	613	547	-	-
	H-Ni / H-Mn	-	-	517	335	175
10	L-Ni / L-Mn	-	-	580	348	162
	H-Ni / L-Mn	-	-	542	376	138
	L-Ni / H-Mn	-	-	553	366	186
	H-Ni / H-Mn	-	-	513	370	142
						(°C)

1°C/s Microstructures

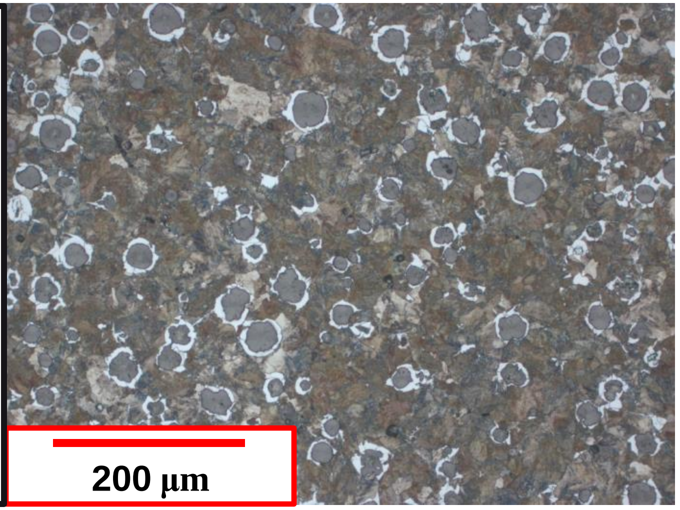
	L-Ni	H-Ni	
L-Mn			

L-Mn

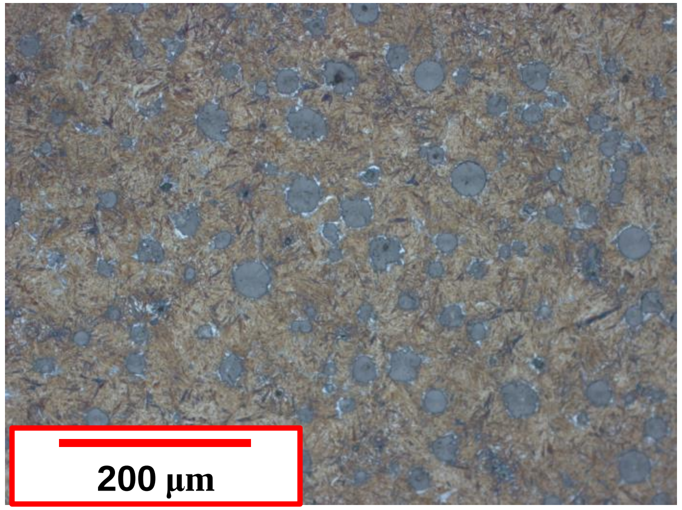
Graphite: 10.0 ± 0.8%
Ferrite: 4.7 ± 0.9%
Pearlite: 85.3%

20 ± 0.4 HRC

L-Ni:



H-Ni:



Graphite: 10.2 ± 0.6%
Ferrite: 0.6 ± 0.2%
Bainite: 43.9 ± 0.9%
Martensite: 45.4 ± 0.9%

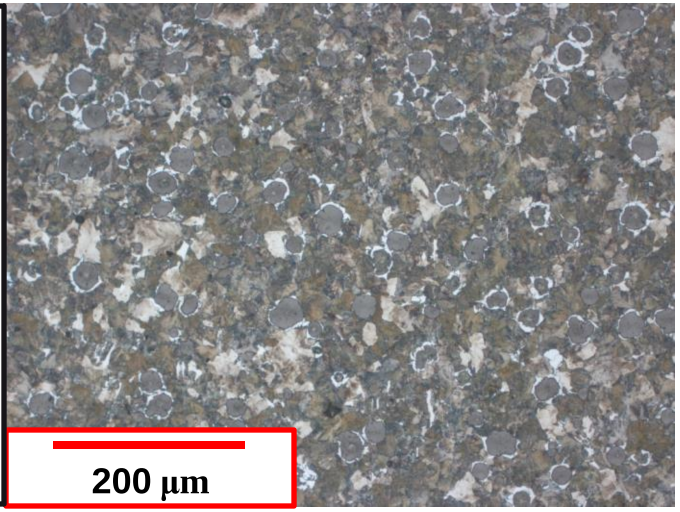
49 ± 0.3 HRC

H-Mn

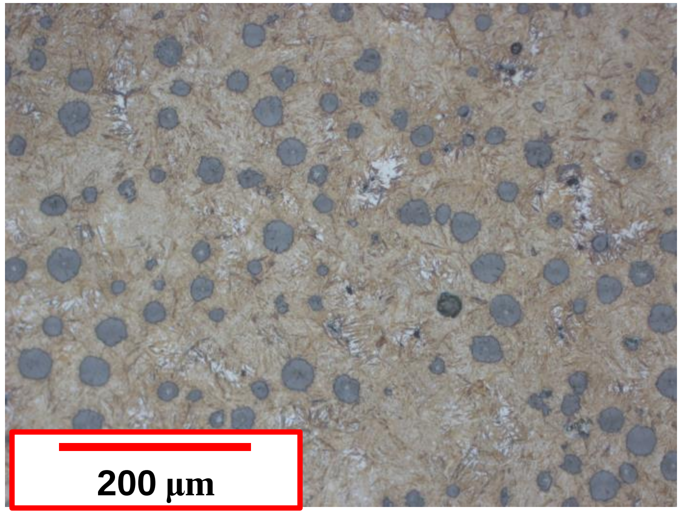
Graphite: 9.0 ± 0.3%
Ferrite: 2.7 ± 1%
Pearlite: 88.3%

26 ± 0.7 HRC

L-Ni:



H-Ni:



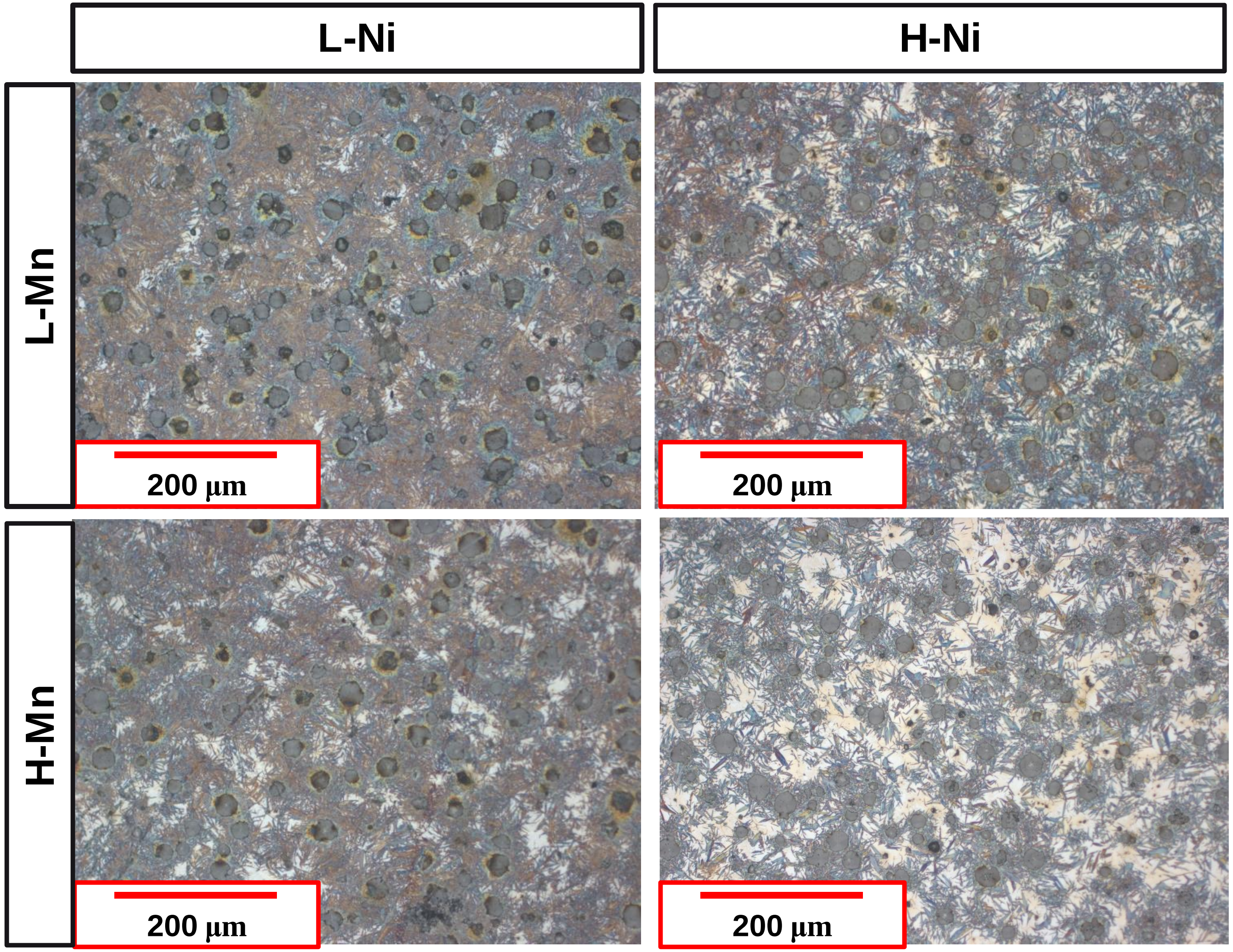
Graphite: 9.5 ± 0.6%
Austenite: 1.7 ± 1%
Bainite: 40.9 ± 2%
Martensite: 47.3 ± 2%

51 ± 0.5 HRC

10°C/s Microstructures

Graphite: 9.3 ± 0.6%
Austenite: 3.9 ± 0.8%
Bainite: 68.3 ± 0.8%
Martensite: 16.5%

54 ± 0.2 HRC



Graphite: 9.8 ± 0.6%
Austenite: 9.1 ± 2%
Bainite: 58.0 ± 0.7%
Martensite: 23.1%

49 ± 0.6 HRC

Graphite: 8.7 ± 0.4%
Austenite: 8.3 ± 1%
Bainite: 66.1 ± 0.7%
Martensite: 16.4%

54 ± 0.4 HRC

Graphite: 8.6 ± 0.6%
Austenite: 22.1 ± 4%
Bainite: 53.3 ± 1%
Martensite: 16.0%

43 ± 0.3 HRC

Ni vs Mn Additions on IL DI

Nickel

- H-Ni content promotes more austenite stability in IL DI with retained austenite easily attainable
  - Retained austenite likely to transform in Martian application due to reduced atmospheric temperature
- Significant hardness benefits
- Readily available from meteorites, asteroids, etc.

Manganese

- H-Mn does not give significant variation in property
  - Small window from L-Mn to H-Mn value due to Mn composition limits
- Slight hardness increases
- Little microstructural change
  - Baseline L-Mn seems sufficient, but additions could be made depending on desired properties
- May be available in some areas for additions to IL composition

Summary

- Dilatometry showed similar phase transitions with significant grouping of H-Ni materials for property variation
  - Additional Mn may not be worthwhile due to minimal effects from baseline L-Mn
- Hardness and microstructure showed IL DI responds well to heat treatment
  - With Ni additive, increased cooling rates will result in significant retained austenite
  - Likely that Martian/Lunar surface temperatures are cool enough to allow complete martensite transition
- The use of IL-Fe and Bosch C as casting feedstock could produce numerous ductile iron grades with minimal additions and some cooling rate control or post processing
- *In summary, the use of Bosch C with IL-Fe is likely a viable option to manufacture ductile iron on the Lunar or Martian surfaces, with some limitations*

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