ISRU Iron Alloys: Properties and Testing on Iron Produced by Hydrogen Reduction of Lunar Regolith Simulant

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Agenda

- Objectives
- Background
  - Elements of Interest on the Moon
  - Metal Isolation
  - Phosphorus in Steel
- Experimental Work
  - Experimental Process

Objectives

- Understand the effects of phosphorus on ISRU metals activity

- Provide mechanical property data for potential designs

Acknowledgements

- Pioneer Astronautics: Moon to Mars Oxygen and Steel Technology (MMOST)
  - Phase II Sequential SBIR

Elements of Interest on the Moon

- Why Iron?
  - Iron is the first useful metal to reduce
  - High strength to volume ratio
    - Bearings, gears, tools, stationary components, etc.
  - Long term, carbon for alloying to steel
- Focus on Hydrogen reduction
  - Could apply to other reduction processes

Difficulty

Major Elements	Weight % Highlands	Weight % Maria
Oxygen	45	45
Iron	6	15
Silicon	21	21
Titanium	<1	1-5
Magnesium	5.5	5.5
Aluminum	13	5
Calcium	10	8

L. Haskin and P. Warren, "Lunar Chemistry," in Lunar Sourcebook, New York, Cambridge University Press, 1991

Limitations Imposed by the Lunar Environment

- The cost to deliver material to the Moon will be massive
  - Reagents will be cost-prohibitive to replace
    - Limited to “closed loop” processes
  - Alloying elements will need to have a massive effect to justify their cost
    - Potentially favors low atomic number elements

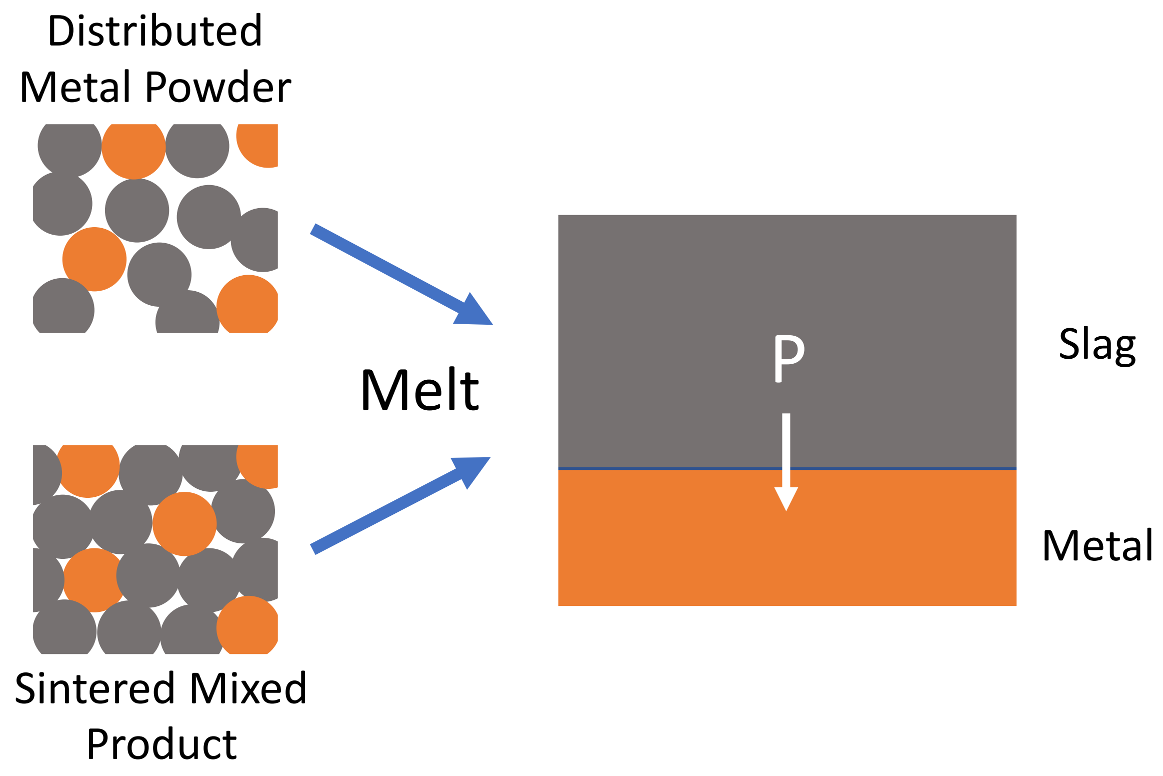
Chemistry from Hydrogen Reduction

- Produced by Pioneer Astronautics MMOST system
- Chemistry is effectively pure iron with phosphorus
  - Not a cast iron
  - Metallurgically a very low carbon steel

Major Elements	H2 Reduction Iron	Weight % Maria
Oxygen	0	45
Iron	98.8	15
Silicon	0	21
Titanium	0	1-5
Magnesium	0	5.5
Aluminum	0	5
Calcium	0	8
Phosphorus	0.9	~0.5

Metal Isolation from Reduction

- Reduction produces a mixed metal-slag product
  - Powder
  - Sintered
  - Liquid
- Liquid products allow density separation
- Have a liquid-liquid interaction between slag and metal



Phosphorus in Steel

- Causes cold work embrittlement
  - Segregates to grain boundaries (GB) and weakens them
  - Leads to brittle failure (low ductility)

- Upper limit is typically 0.04-0.08wt%
  - ~10x a standard steel limit

Phosphorus Mitigation

Terrestrial steelmaking process:

- Reduce P: by controlling ore and low P "metallurgical" coal
- <u>Remove P: using basic slag (CaO and MgO rich) during melting</u>
- Counteract P: carbon and other alloying elements can strengthen GB
- *Remove P: Hydrogen treating of ore can remove P*
    - *Only partial removal (13-76% reduction)*
    - *TRL 2-4*

Lunar process:

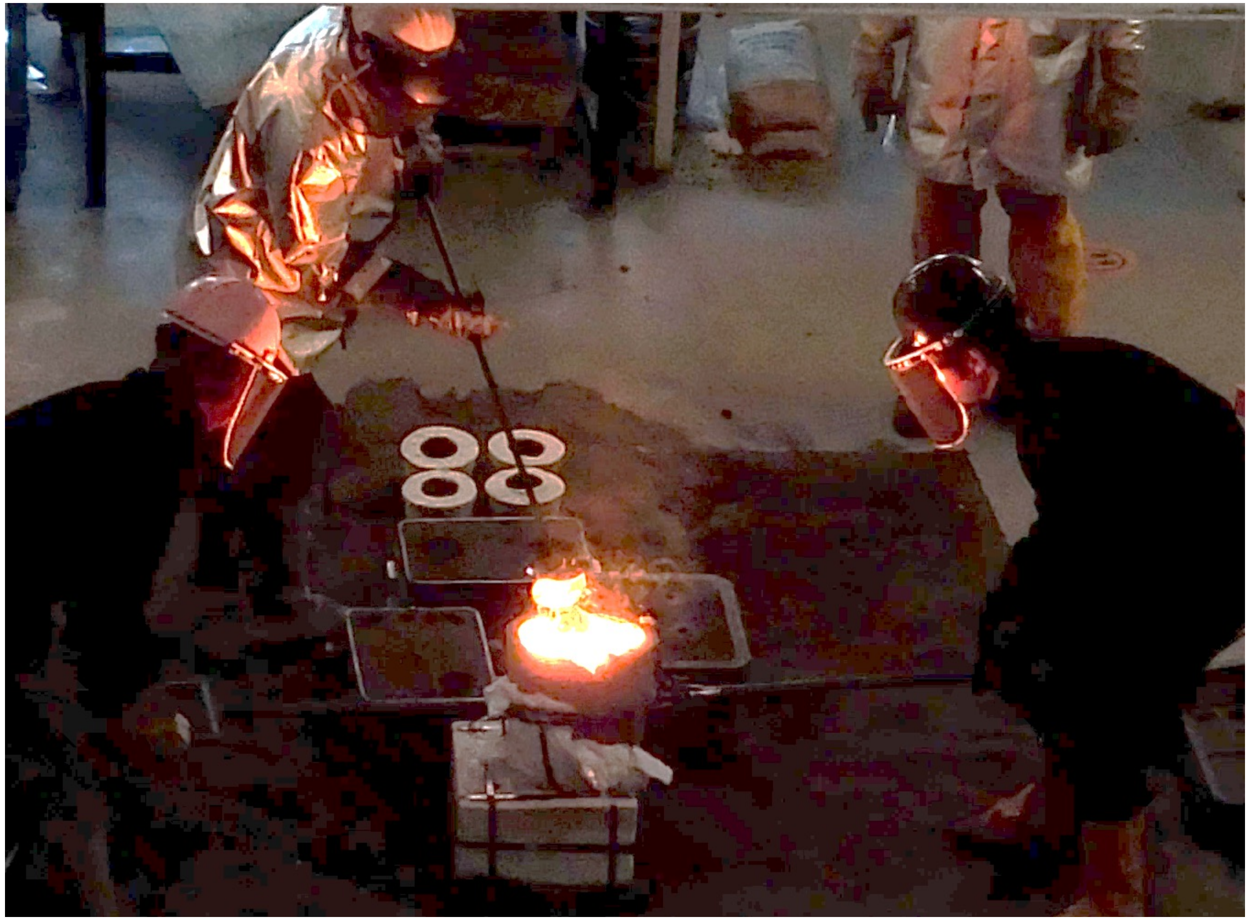
- Reduce P: no "pure" ore bodies exist.
    - Gangue minerals (KREEP) will contribute P
- Remove P: TiO_2 from ilmenite ($FeTiO_3$) and SiO_2 results in acidic slag
    - Increases P concentration in the metal
    - CaO rich mineral deposits (limestone) not available on the Moon
- Counteract P: alloying elements are expensive
- *Remove P: Hydrogen Reduction is already utilizing hydrogen gas*

<u>Lunar processes are NOT well suited for handling P contamination</u>

Experimental Work

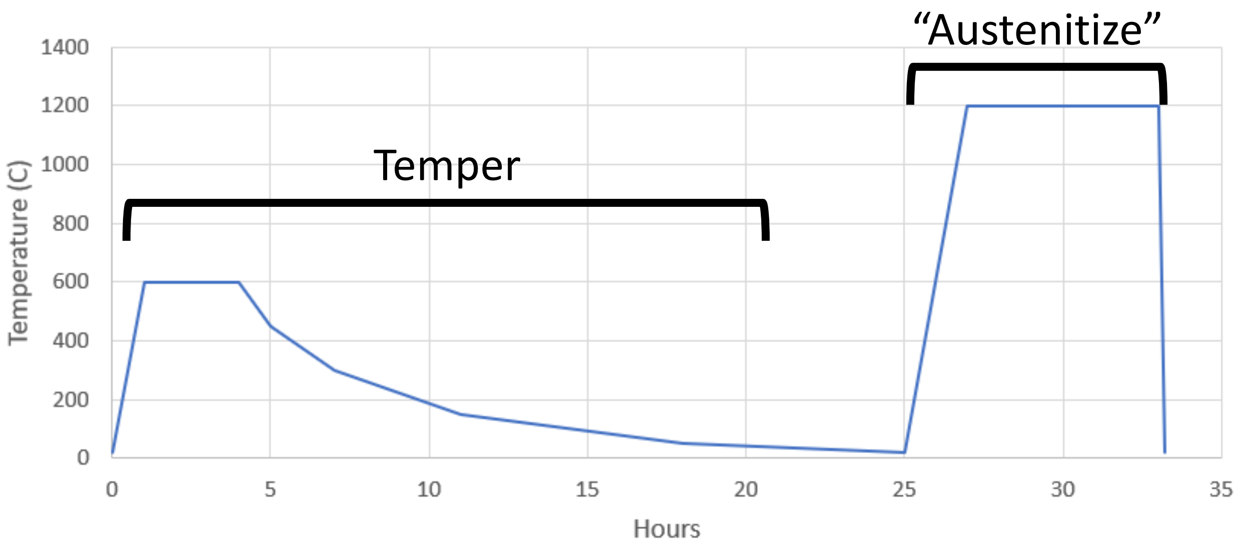
Analog lunar alloys

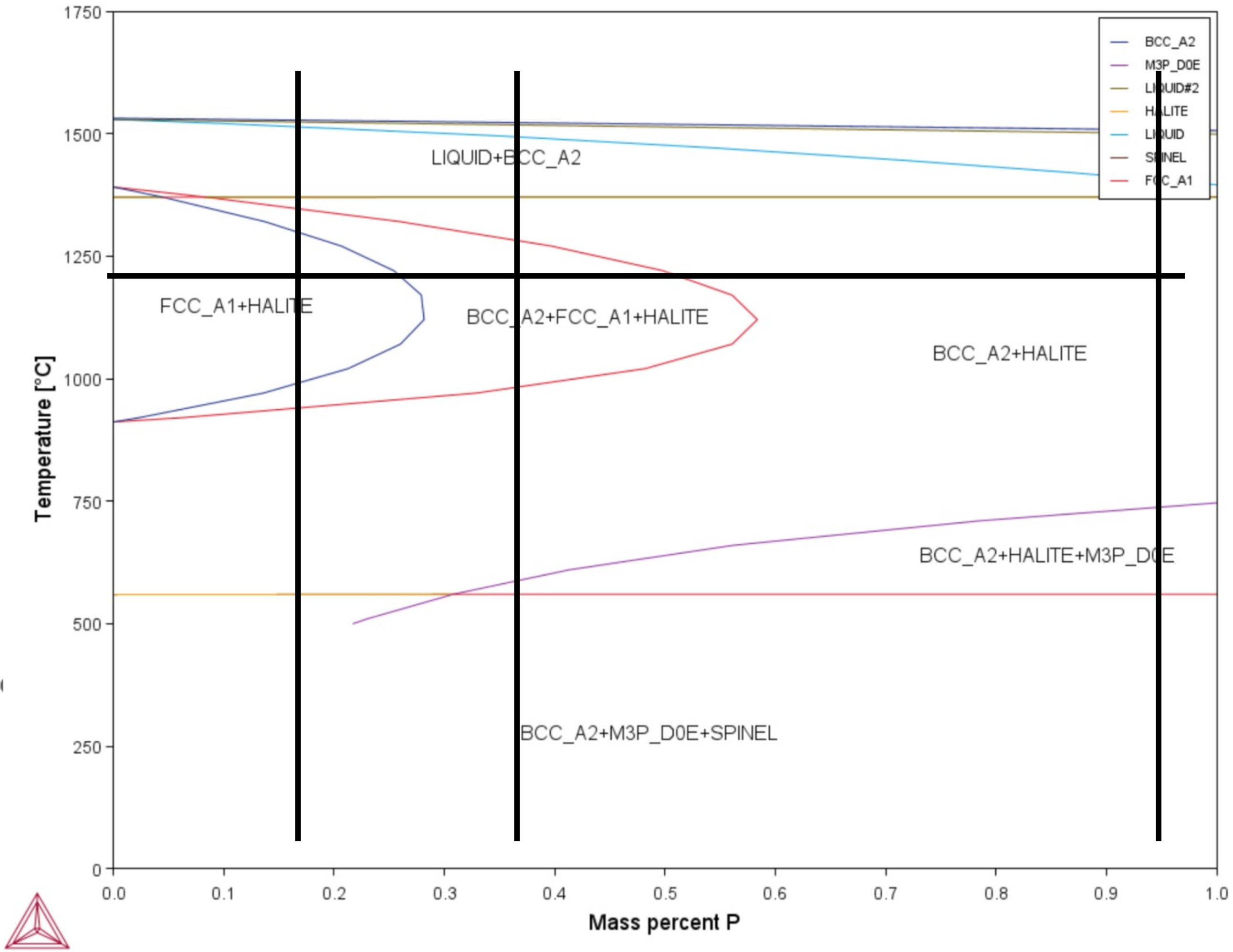
- Goal: Produce a ductile, high-phosphorus alloy
  - Allows conversion into feedstock
- Focus on heat treatment
  - Avoids costly material brough from Earth
- Produced 3 steel alloys
  - 0.15 wt%P
  - 0.35 wt%P
  - 1.00 wt%P



Heat Treatment

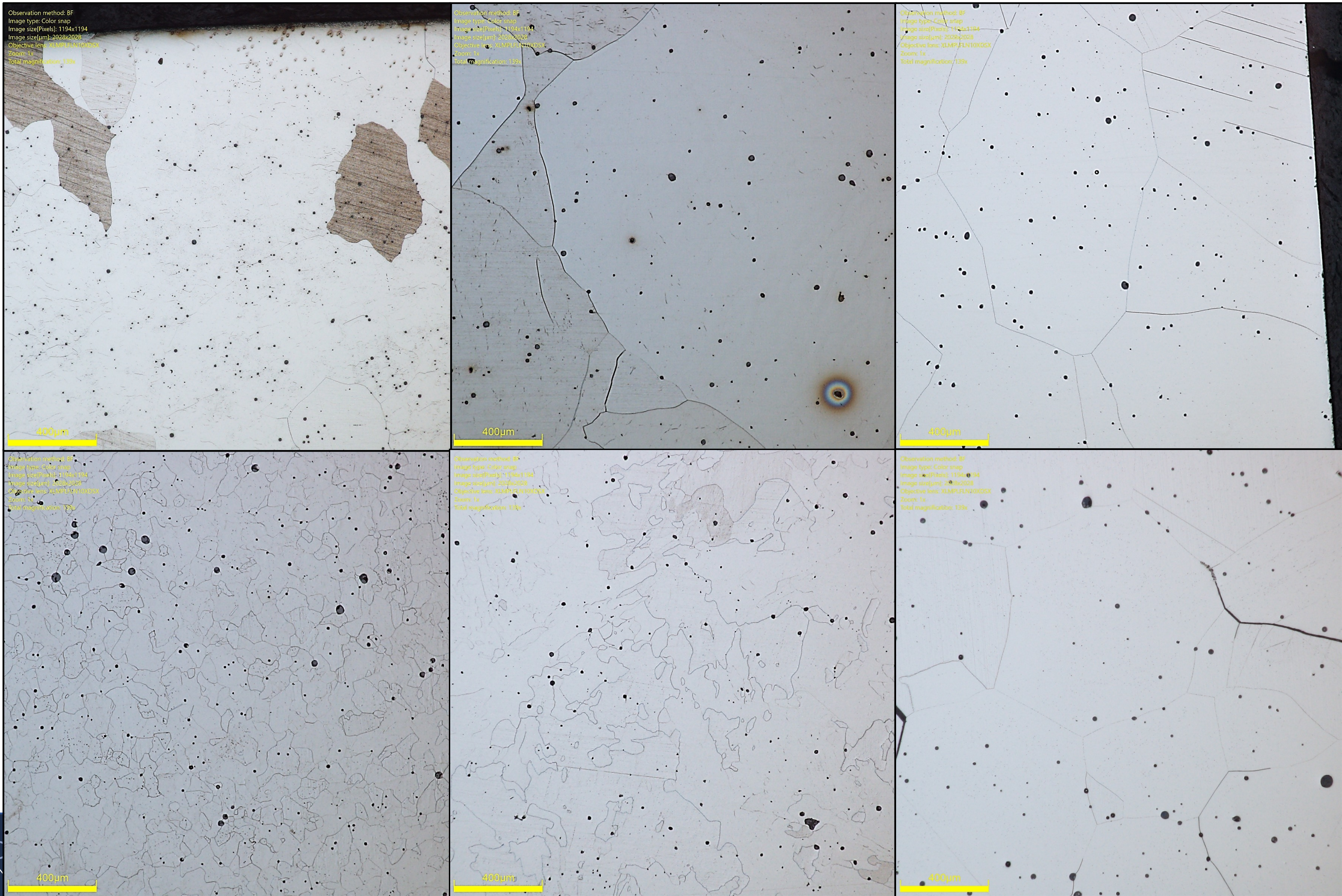
- 8.9cm (3.5in) round cast bars were heated and quenched
- 1200°C to maximize austenite region





Micro-structural Changes

	0.15 wt%P	0.35 wt%P	1.00 wt%P
As Cast			
Heat Treated			



Mechanical Properties

	0.15 wt%P As-Cast	0.15 wt%P Heat Treated	0.15 wt%P Forge + Heat Treat	0.35 wt%P As-Cast	0.35 wt%P Heat Treated	0.35 wt%P Forge + Heat Treat	1.00 wt%P As-Cast	1.00 wt%P Heat Treated	*1026 Hot Rolled*
Hardness (HRV)	121	127	121	146	158	154	231	218	*131*
Yield Stress (MPa)	207	261	219	241	271	286	-	-	*240*
Ultimate Tensile Stress (MPa)	285	398	393	301	329*	447	-	-	*440*
Strain at UTS	0.15	0.19	0.23	0.06	0.03	0.21	-	-	*Total Strain 0.49*

MatWeb – AISI 1026 Steel, hot rolled, 19-32 mm (0.75-1.25in) round

Conclusions

- Iron from Hydrogen Reduction will have elevated Phosphorus
  - 5x-10x higher than conventional steel alloys
  - Likely a concern for other reduction processes

- A process path to produce a workable high-phosphorus iron alloy was developed
  - Demonstrated at 0.35 wt%P
  - Likely possible up to 0.45 wt%P

- Recent research has shown a potential path to reach these phosphorus levels

Questions?