A Study of an Alternative Carbon Source to Improve Environmental Sustainability in Steel Production

Blake Stewart[1,2], Haley Doude[1], Terry Taylor[3], Morgan Abney[3], and Hongjoo Rhee[1,2]

[1]Center for Advanced Vehicular Systems, Mississippi State University, Mississippi State, MS 39762

[2]Department of Mechanical Engineering, Mississippi State University, Mississippi State, MS 39762

[3]Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, AL 35812

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MATERIALS SCIENCE & TECHNOLOGY

Motivation

- One ton iron from blast furnace = 0.33~0.44 ton CO_2[12]
- Global iron and steel CO_2 emissions = **1.7 gigatons**[8]
- Environmental regulations are requiring manufacturers to reduce oxocarbon emissions.
- High quality steel alloys with smaller carbon footprint.
- Potential for production cost savings.

Benxi Steel Plant, China, 2000.
(Credit: Jon Bower Pollution/Alamy Stock Photo)

Overview

- Biomass coal limited in production and cost [3,10].
- ULCOS CO_2 capture method = 10~15% reduction[11]
- U.K. recently funded decarbonization in steel industry[9].
- Coal has been generated from CO_2 using liquid metals[2].

- Two different ferrous alloys are manufactured with novel carbon source compared to conventional to determine viability as steel carbon source.
- Alternative carbon was produced via a carbon sequestration system.
- Mechanical and microstructural investigation revealed comparable metallurgical properties.

Comparison of Elemental Carbon

- Conventional and alternative carbon were evaluated before alloying.

- Investigation methods
  - X-Ray Powder Diffraction (XRD)
    - Allotropy
  - Field Emission Scanning Electron Microscopy (FE-SEM)
    - Morphology

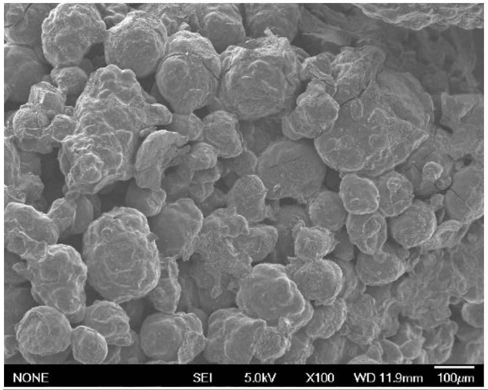
Conventional Carbon

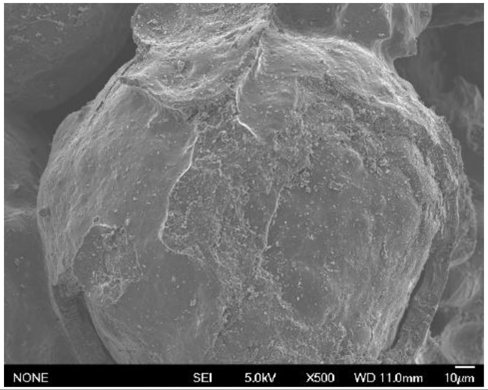
Alternative Carbon

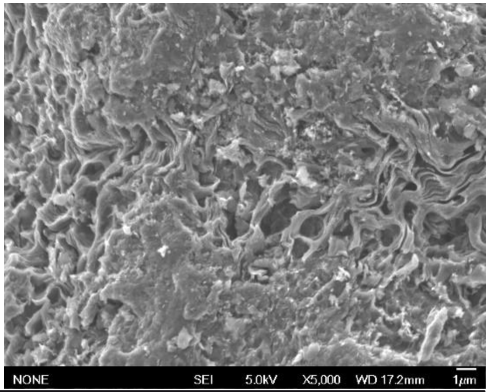
SEM reveals significant differences in morphology

X100 | X500 | X5000

Conventional C

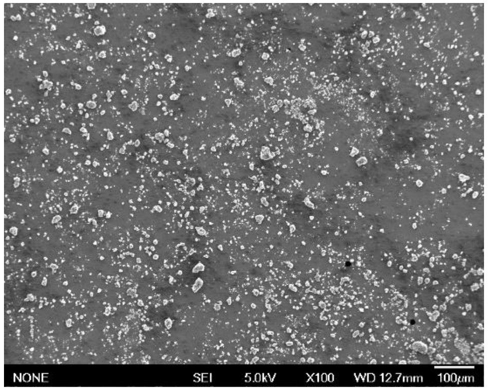


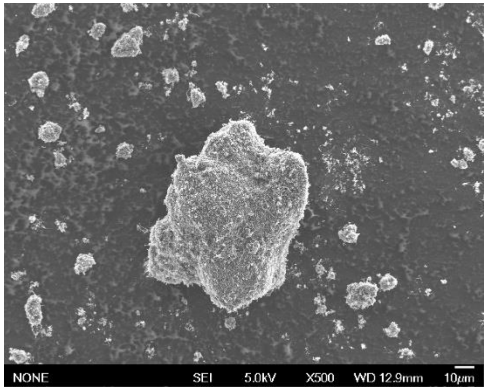


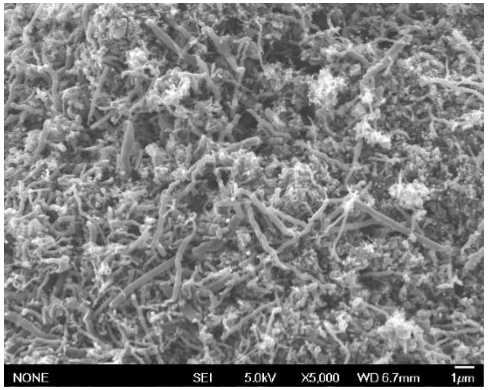


Clumps of spherical particles, 80-150μm

Alternative C



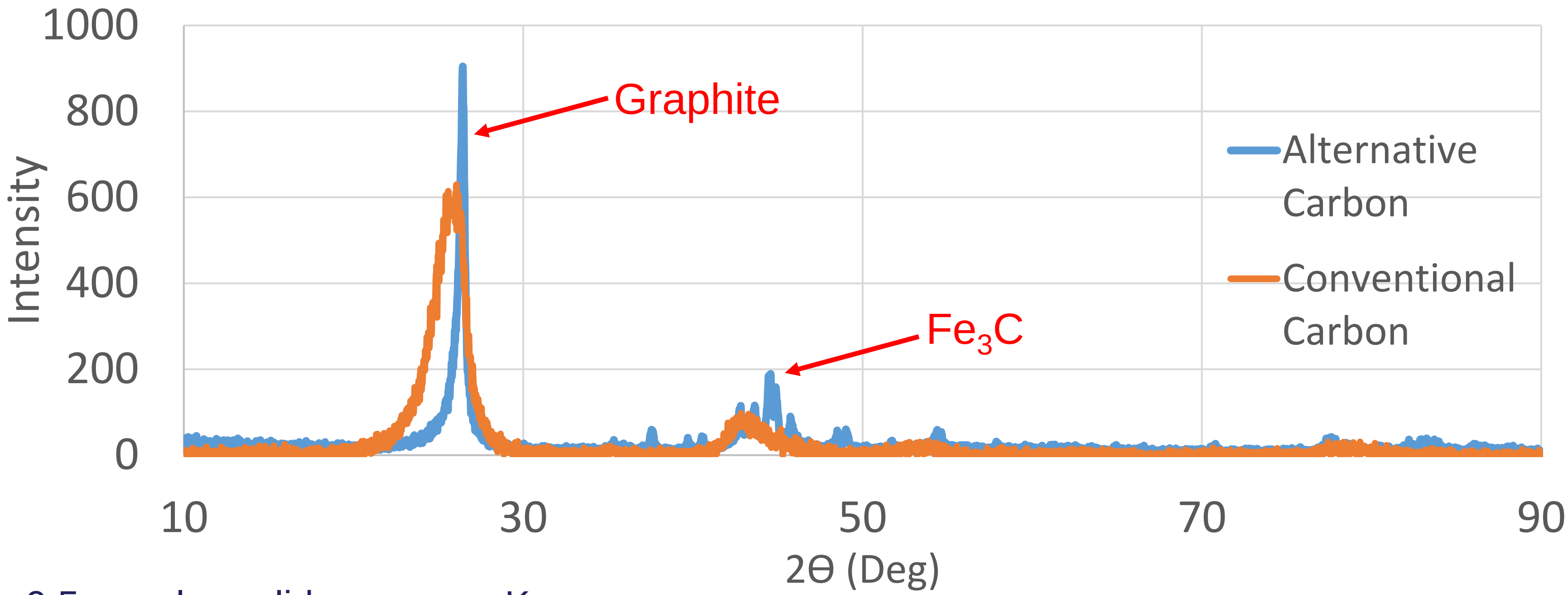




Tangled balls, 10-75μm

XRD shows similar crystalline structure

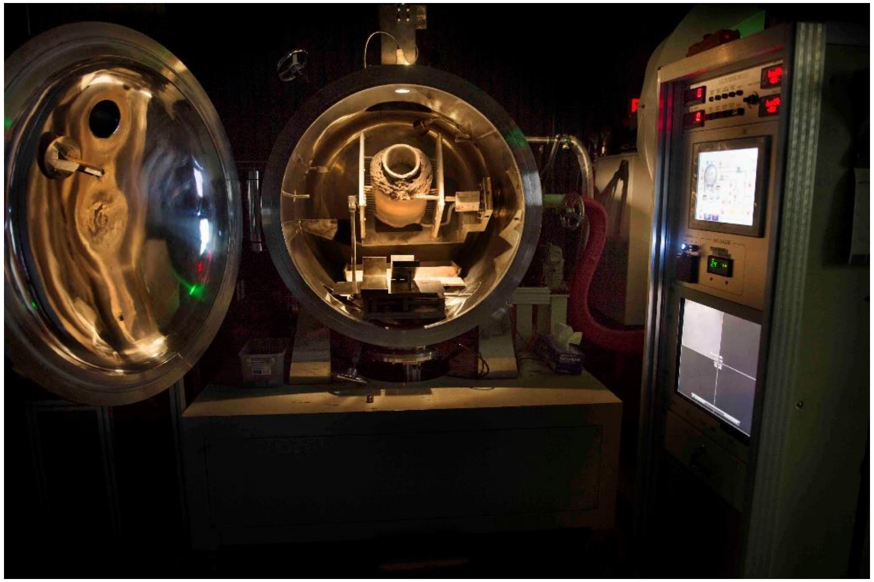
- Conventional Carbon
  - Graphitic carbon
    - 26.1°
  - Peak shift and broadening likely due to grinding prior to scan[1]
- Alternative Carbon
  - Graphitic carbon
    - 26.4°
  - Cementite Fe_3C
    - 44.6°



0.5mm glass slides, copper K-α wavelength, 10-90 degrees 2θ

Comparison of Produced Ingots

- Two ferrous alloys were produced using each carbon source
  - Low Carbon
    - AISI 1020
  - High Carbon
    - Gray Cast Iron



Vacuum Induction Melting Furnace (VIMF)

- Investigation methods
  - Chemical composition
  - Light microscopy
    - Phase fraction, grain size
  - Mechanical performance
    - Quasi-static tension/compression, 0.001/s until fracture
    - Brinell and Rockwell-B Hardness (additional HRC for cast iron)

Low Carbon Steels

- Cast in Vacuum Induction Melt Furnace (VIMF)
- Target composition
  - Carbon (C): 0.2 wt.%
  - Silicon (Si): 0 wt.%
  - Manganese (Mn): 0.45 wt.%
  - Iron (Fe): balance
- Hot rolled to 0.5”
  - 1250°C austenitizing
  - Air cooled
- **Analysis on as-rolled condition**

Hot Rolling using In-house Reversing Rolling Mill

Low carbon steel micrographs

3-D views of low carbon steel microstructures

Conventional C

Alternative C

Rolling Direction

Low carbon steel grain sizes

- Average phase fractions
  - Conventional:

    82.6 ± 1.43 % ferrite

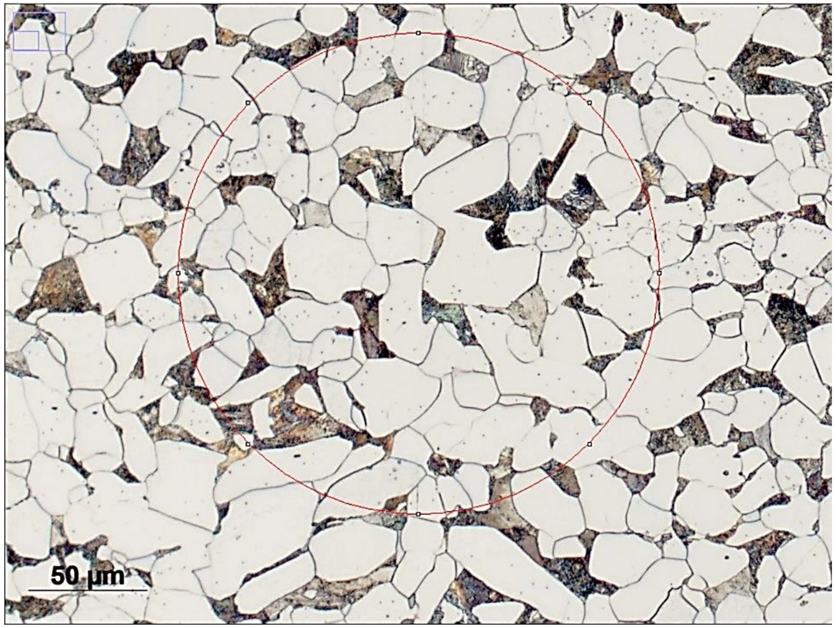
    17.4 ± 1.43 % pearlite
  - Alternative:

    81.7 ± 0.627 % ferrite

    18.3 ± 0.627 % pearlite
- Average grain sizes
  - Conventional:

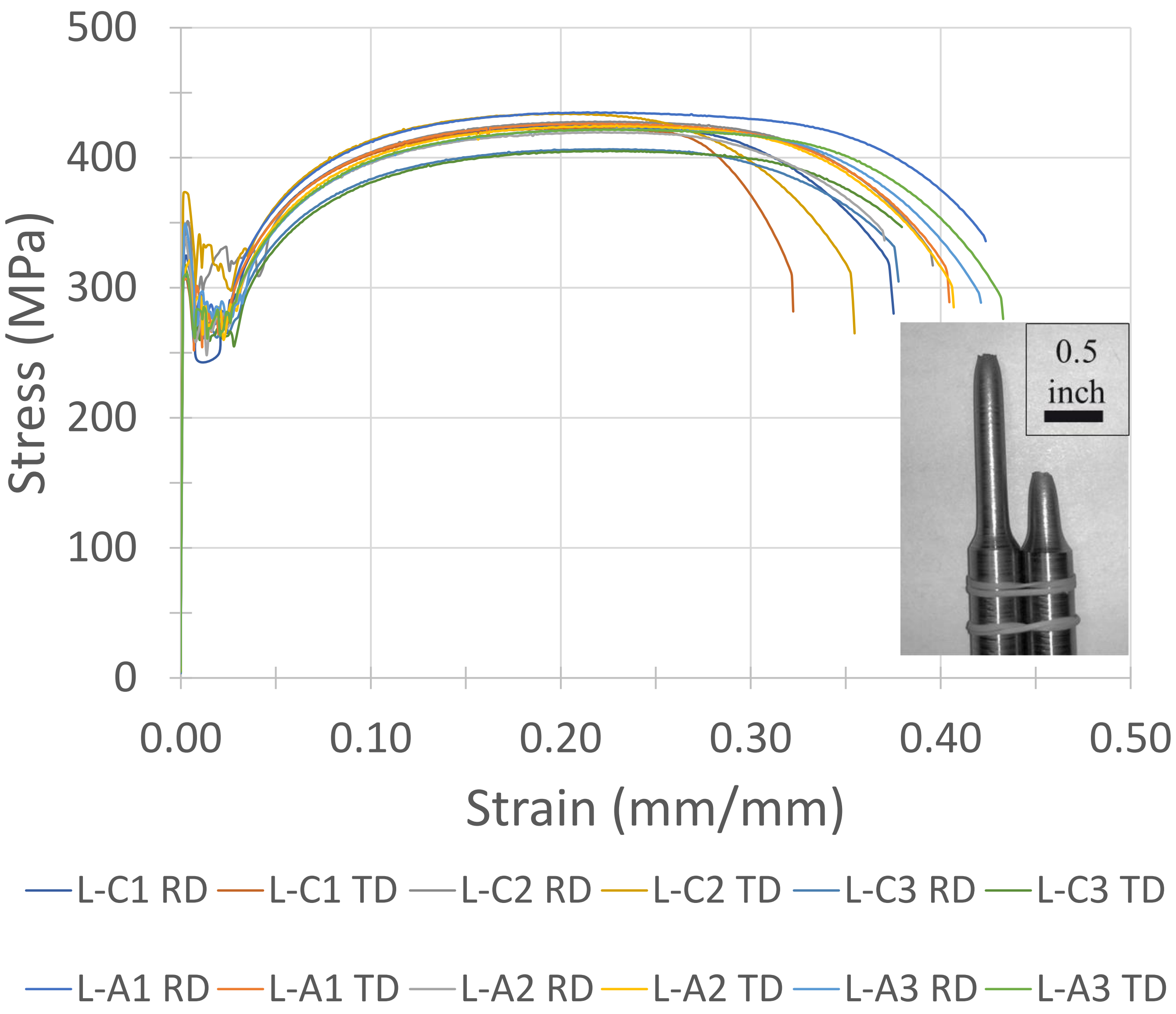
    33.4 ± 4.95 µm (ASTM: G= 6.5-7.0)
  - Alternative:

    36.6 ± 1.680 µm (ASTM: G= 6.5-7.0)



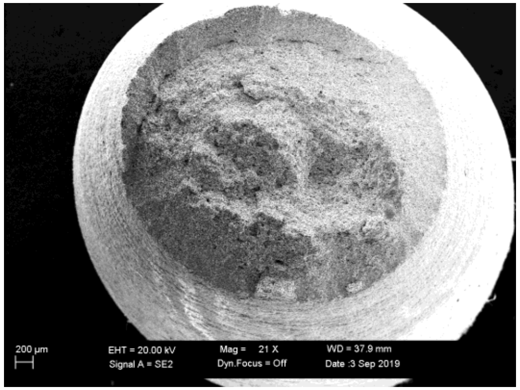
Grain size analysis of low carbon steel using conventional C by ASTM E112-13: Planimetric (Jefferies) Procedure

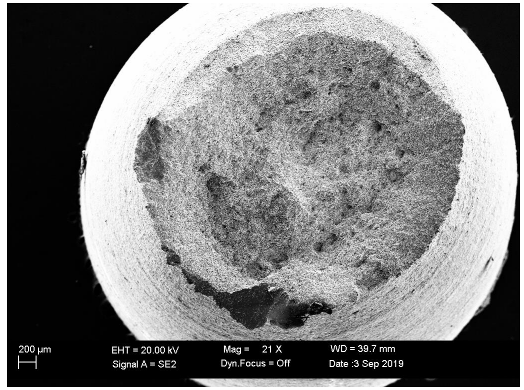
Low carbon steel tensile testing results

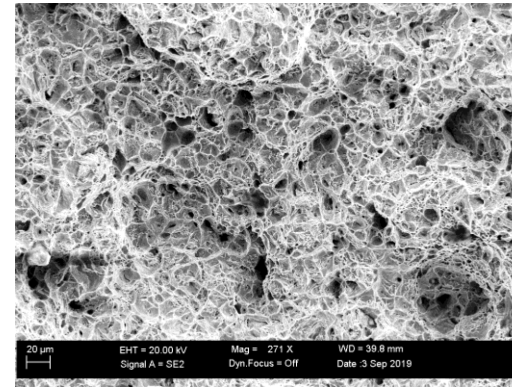


- L-C2 slightly higher σ_{uys} due to smaller grain size
  - Grain size reduced from colder rolling issue
- Similar to standard values for performance

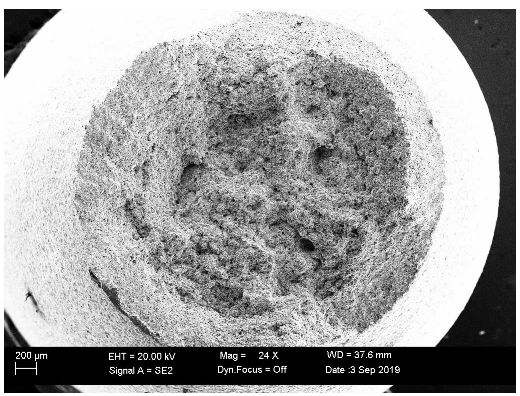
Low carbon steel tensile fracture surfaces

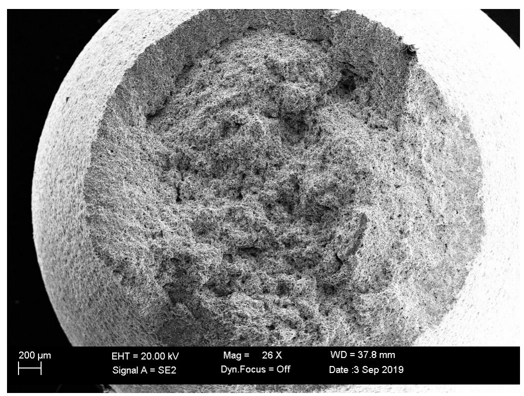


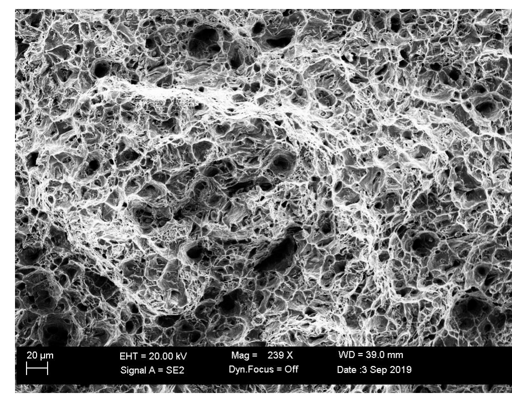




Fracture surfaces of Conventional Carbon tensile specimen







Fracture surfaces of Alternative Carbon tensile specimen

Low carbon steel hardness

- Average hardness
  - HB, HRB, and
  - HRC (cast irons only)
- Industry standard for AISI 1020 around 111 HB

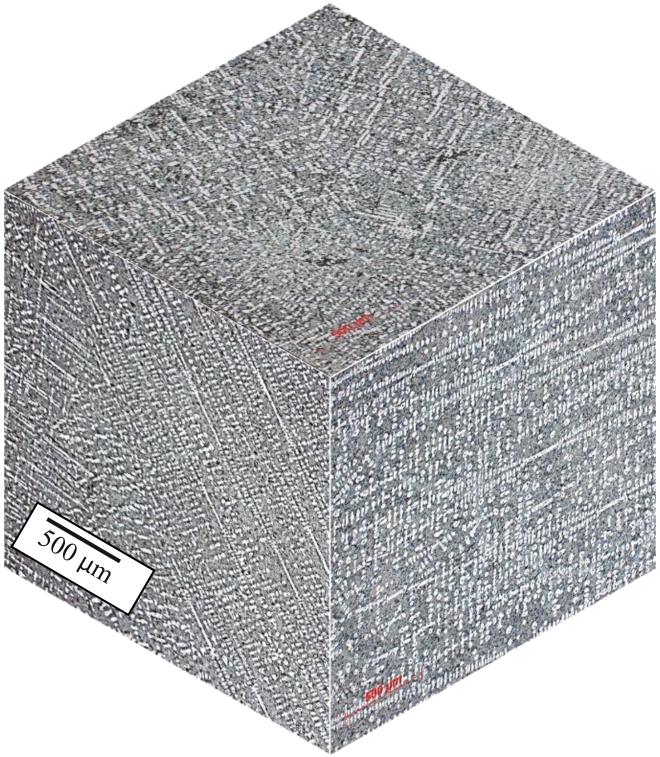
Alloy	Hardness	
	HB	HRB
L-C	116 ± 6.432	60.14 ± 7.540
L-A	113 ± 5.481	60.92 ± 3.103

Cast Irons

- Cast in Vacuum Induction Melt Furnace (VIMF)
- Target composition
  - Carbon (C): 3.5 wt.%
  - Silicon (Si): 2.5 wt.%
  - Manganese (Mn): 0.45 wt.%
  - Iron (Fe): balance
- **Analysis on as-cast condition**

Cast iron micrographs

- Conventional C

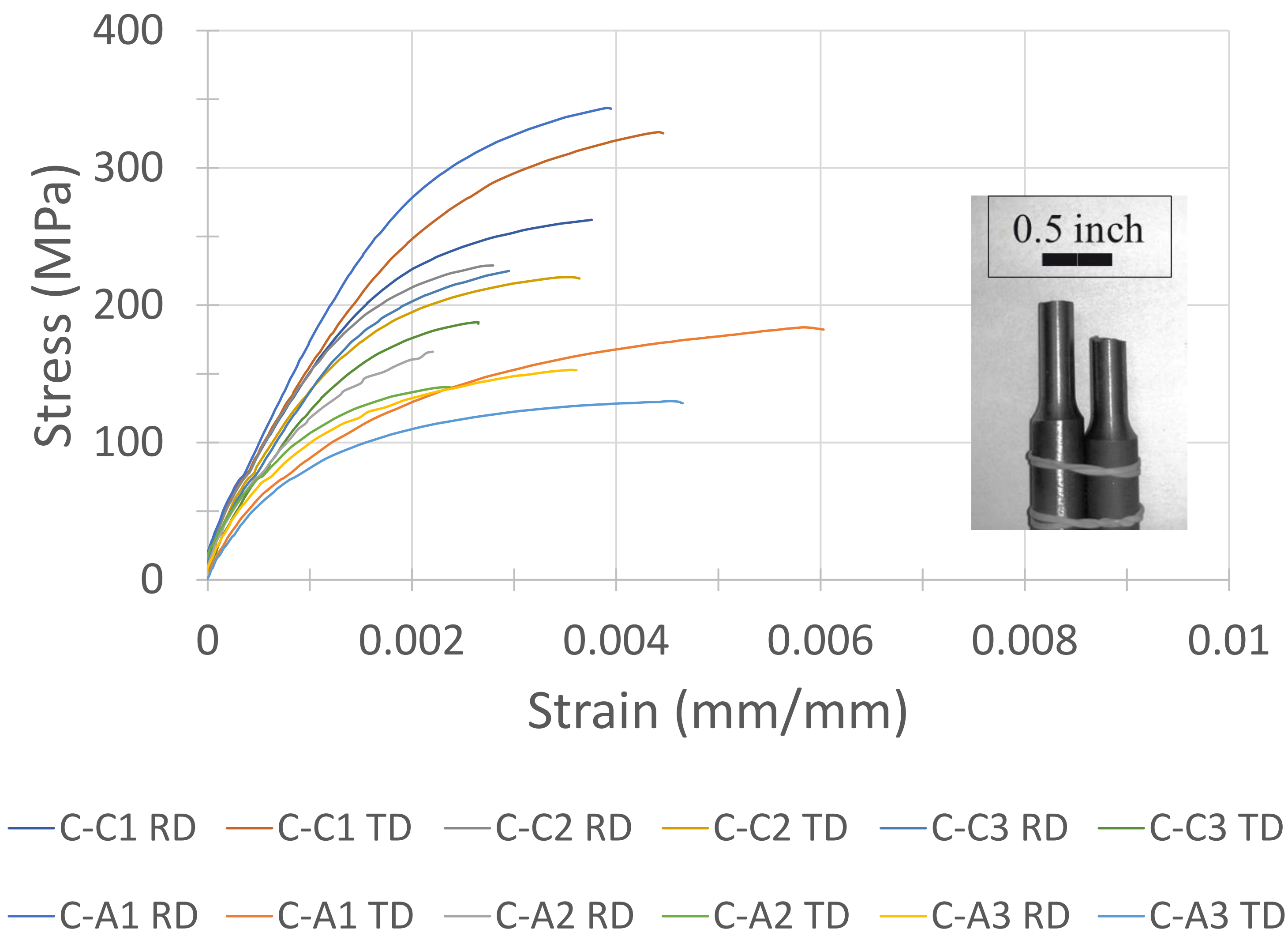


Casting Direction

- Alternative C

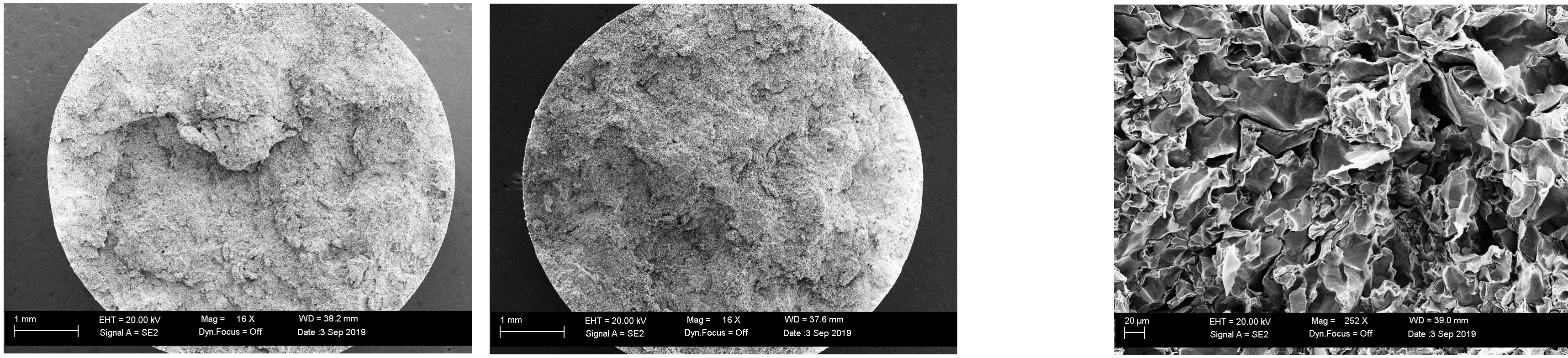
Phase fraction / Grain structure:
Distribution D, Class 7

Cast iron tensile test results

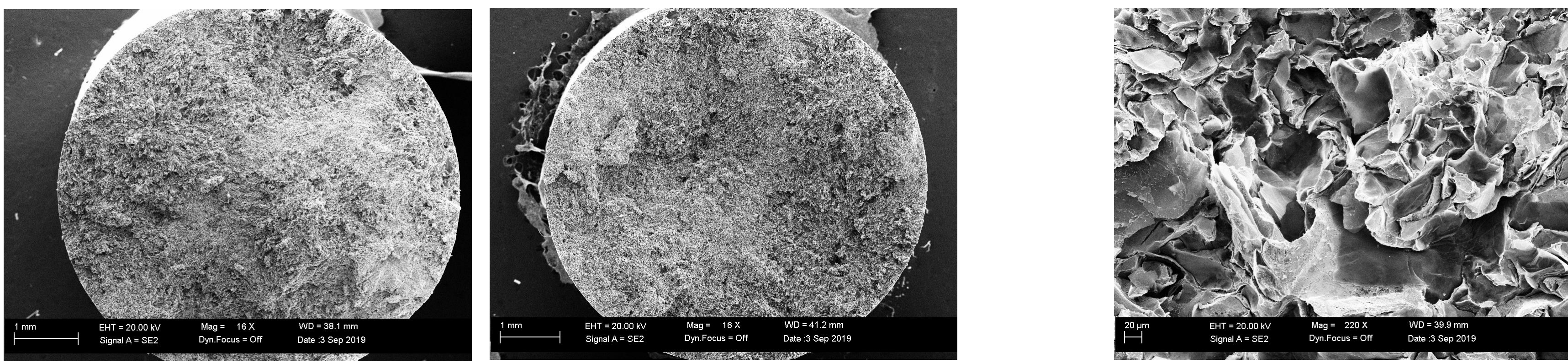


- Significant variability
- But, consistent when testing from the same ingot

Cast iron fracture surfaces



Fracture surface of Conventional Carbon tensile specimen



Fracture surface of Alternative Carbon tensile specimen

Cast iron hardness

- Average hardness
  - HB, HRB, and HRC
- Similar hardness for all cast iron with one exception
  - C-C1: ~250 HB
- Industry range from 120-550 HB

Alloy	Hardness		
	HB	HRB	HRC
C-C	193 ± 48.989	83.11 ± 1.925	4.47 ± 1.220
C-A	167 ± 6.763	82.84 ± 1.830	2.86 ± 1.150

- Similar in composition and hardness to SAE J431 automotive GCI
  - <187 HB

Summary / Discussion

- A novel carbon source was studied to determine if alternative carbon produces similar metallurgical results as conventional carbon
- Two ferrous alloys, 1020 and grey cast iron, were manufactured
- Low carbon alloys show comparable structure and properties for both carbon sources
- Cast iron shows significant variance in properties
  - Believed to be caused by cooling rate inequalities throughout the ingot
    - Cooling significantly affects mechanical properties [6,7]
  - Implies alternative carbon could be used for numerous alloys and different solidification rates and heat treatments
- Mechanical and microstructural investigation reveals comparable metallurgical properties

⇒ **The alternative carbon source showed it is possible to use as the elemental carbon source for steel making**

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