High Performance Electrical and Thermal Conductors

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Project Objective

- Our objective is to characterize the physical, thermal and electrical properties of covetic materials and establish the structure-property-processing correlation using advanced electron and ion microscopy & synchrotron-based X-ray techniques (including 3D tomographic visualization, elemental and chemical mapping, and micro-diffraction-based structural analysis) to investigate the nanocarbon structure, distribution, and carbon/metal interface.

- **There are unique challenges:**
  - Multiple analytical methods are needed to measure carbon content and characterize the microstructure/nanostructure.
  - The carbon distribution in available samples shows high variability.
  - The measured properties also show high variability.
  - Sample histories have not been completely known to this point.

Much is unknown regarding the nature of the nanocarbon phase, its size & spatial distribution, and particularly the structure of the metal-carbon interface at the atomic scale. The unique characterization facilities at the DOE Labs provide an ideal opportunity to study the fine structure of covetic materials and answer some of the fundamental questions about them.

Technical Innovation

- Team includes ANL, ORNL, NETL, and University of Maryland --- utilizing the resources at the DOE Labs and the University to explain the unique properties of covetic materials and develop improved melt practices that produce consistent products for widespread commercialization of covetic materials
  - The combination of analytical tools can unlock critical structural features.
  - The combination of processing equipment can manipulate structure to optimize properties.
- Covetics can be prepared under controlled conditions
  - Sample preparation details, variation in process parameters, etc. are available to compare properties with parent alloys
- Industrial partners to produce large batches (~300 pound heats) of covetics and an end user (one of the largest overhead power transmission cable producers in Americas) are already on-board.

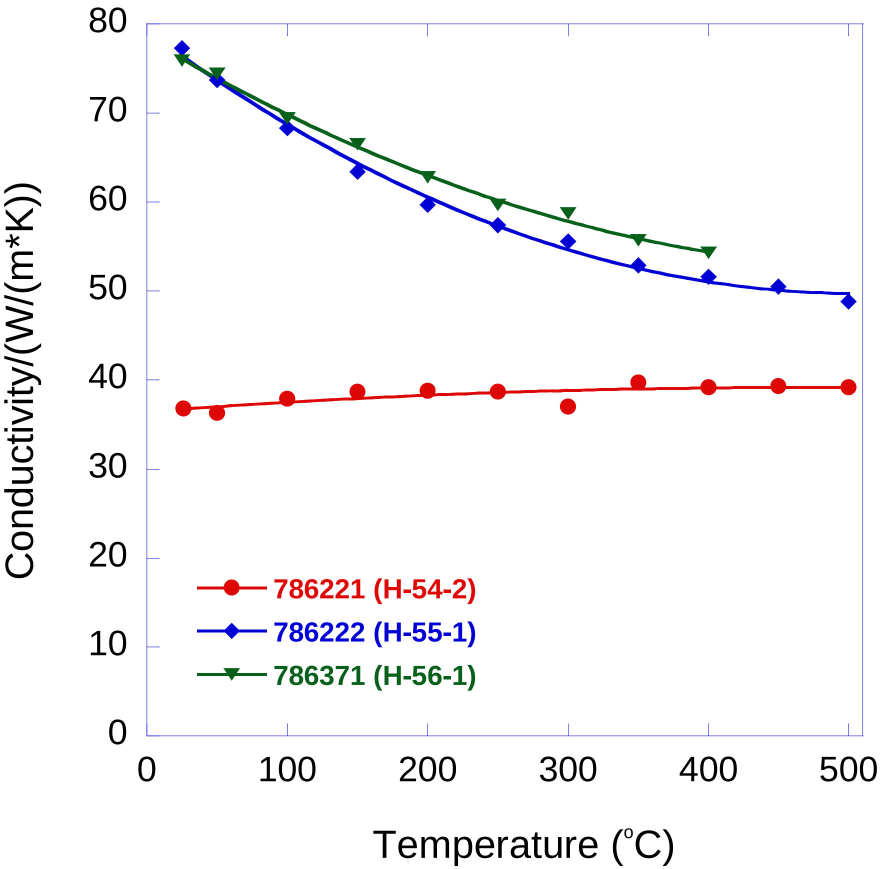
"Extraordinary claims require extraordinary evidence." – Carl Sagan

Technical Approach

- Microstructures are characterized by scanning electron (SEM), high resolution transmission electron (HRTEM), and helium ion (HIM) microscopy to study lattice distortion and distinguish carbon-rich phases, carbon form, oxides, etc.
- Elemental analyses are done by EDXS, XPS, LECO, ICP-OES, DC-PES to determine "free" & "covetic" carbon.
- Nano-tomographic images and CT scans are obtained using hard X-ray nanoprobe station at the Advanced Photon Source.
- Neutron diffraction is done to measure lattice spacing/distortion.
- Thermal expansion, thermal diffusivity, thermal and electrical conductivities are measured to validate the properties.
- The lack of standardization in the covetic conversion process, which has been a problem to this point, is being addressed by the DOE program.
- As part of the overall DOE-EERE requirement, Technology-to-Market (T2M) teams have been created at the National Labs to ensure that the R&D conducted is consistent with the ultimate objective of deploying the technology. Large-scale producer and end-user of the technology are on-board.

This project builds on capabilities at the National Laboratories to advance the development of covetic materials, which could have widespread implications for energy savings in thousands of potential applications.

Results and Accomplishments: Thermal Conductivity of Covetic Grey Cast Iron (ASTM E 1461, Flash-technique, axial direction)



786221 (H-54-2): Mother alloy; Class 25 Grey iron (~3.5 wt.% C) – ASTM E 1999-99

786222 (H-55-1): Mother alloy went thru' conversion process EXCEPT no carbon added during conversion

786371 (H-56-1): Mother alloy went thru' conversion process with 3 wt.% carbon added during conversion

- *High thermal conductivity of steel improve performance of die cast products, increase solidification rates, and reduce shrinkage porosity & hot cracks*
- *Heat exchangers*

- Double the thermal conductivity at room temperature; ~40% increase at 500°C over mother grey iron

Results and Accomplishments: Electrical Resistance of Covetic Copper Films (~30 nm)*

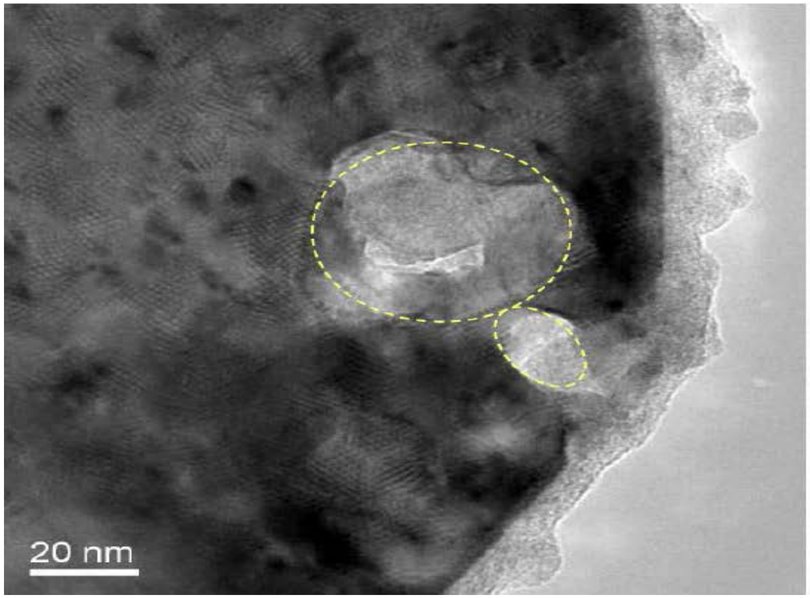
Sample ID	CuC2 (Cu/2% wt. C Covetic)	Cu99 (Cu-Parent metal)
test1 (Ω)	0.1317	0.1951
test2 (Ω)	0.1340	0.1966
test3 (Ω)	0.1276	0.2010
test4 (Ω)	0.1270	0.1893
test5 (Ω)	0.1327	0.1897
Average (mΩ)	130.59	194.34
Stand. Dev (mΩ)	2.82	4.44
Sheet Resistance (mΩ/□)	**591.89**	**880.80**

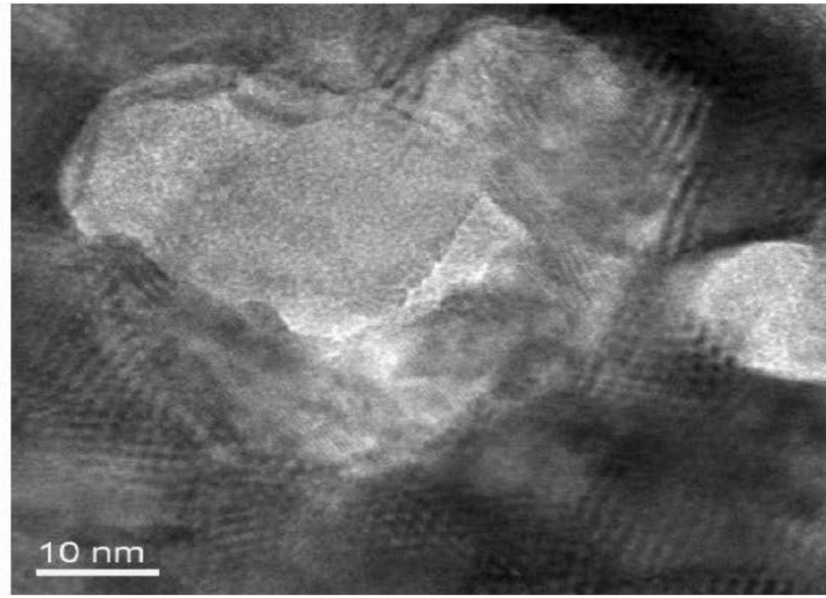
Sheet resistance of covetic copper film (CuC2) is ≈33% lower than that of Cu99 (parent metal) film

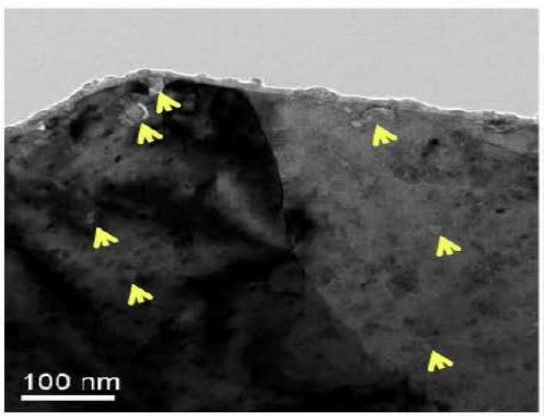
Electrical conductivity of covetic copper is significantly (≈33%) enhanced compared to its parent copper

*Invention Disclosure on covetic processing reported to DOE

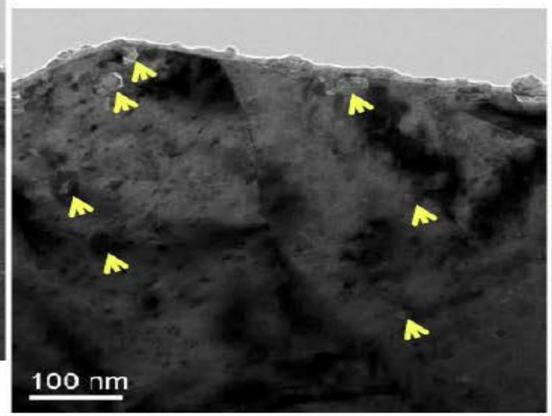
Results and Accomplishments: HRTEM of nano-carbon clusters in covetic copper alloy (Cu-4T)



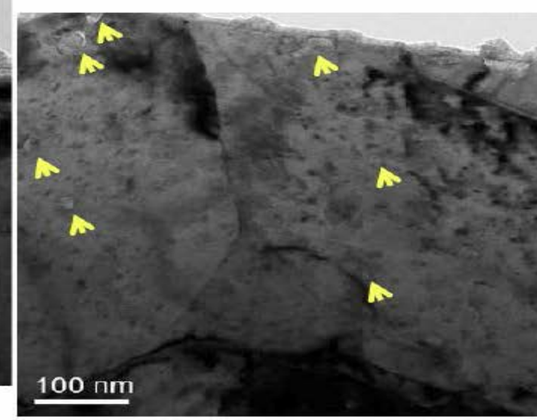




Tilt angle = 0°



Tilt angle = 15°



Tilt angle = 30°

Yellow arrows highlight nano-carbon clusters in a Covetic Cu alloy.

Future Plans & Challenges

- Characterize the electrical and thermal properties, explore the relationship between stress fields and conductivity, and explore the directionality of thermal and electrical conductivity.
- Use APS synchrotron source to visualize covetic nanostructures with high spatial resolution. Conduct spectroscopic elemental and chemical mapping and micro-diffraction-based structural analysis.
- Perform neutron diffraction to study lattice expansion/distortion that offers one explanation for the improved properties of covetic materials.

Challenges:

- Develop fundamental understanding of covetic conversion in order to improve the process
- Improve melt practices to produce consistent products for wide spread commercialization of covetic materials
- Establish methods for materials validation & deployment

This technology is expected to have a market pull due to the unique properties that solve a number of existing problems.