Fabrication of Advanced Nanocarbon-Metal Composites for Improved Energy Efficiency

DE-EE0008313

University of Maryland/ GDC Industries/ARL/General Cable

Project Period 1

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Overview

Timeline

- EERE Award Start date: May 1, 2018
- BP1 End Date: October 31, 2019
- Projected End date: April 30, 2021
- Project ~30% complete

Budget

	BP 1 (18 months)	BP 2 (9 months)	BP 3 (9 months)	Total Planned Funding (36 months)
DOE Funded	957,985	602,681	528,981	2,089647
Project Cost Share	267,908	136,068	120,997	524,973

Barriers

- No standardized method for determining the level of converted carbon
- Tedious procedure to demonstrate a successful conversion:
  - Microscopy (TEM, SEM, AFM)
  - Spectroscopy (XPS, EELS, Raman)
  - Thermophysical properties
  - Material must be hot deformation processed to consolidate porosity
- Small business partner also has difficulty providing material that is consistently converted

Partners

Our team consists of:

- University of Maryland (lead) (fabrication and characterization)
- Army Research Laboratory (ARL) (electrical, mechanical characterization)
- GDC Industries (small business) (fabrication)
- General Cable (major supplier) (electrical and mechanical characterization)
- Consultations with Argonne and NETL Albany

Project Objectives

Aligned with AMO's MYPP Target 5.2: ***Develop scalable manufacturing processes for a range of materials with 50% or greater improved thermal or electrical conductivity.***

Problem

- A process has been invented by a small business: it significantly improves thermal and electrical conductivity of Al, Cu, Ag, Au, Fe, Pb, etc.
- This *Covetic conversion* has been reproduced at National Labs and Universities
- Process is potentially low cost and scalable, but. . .
- Properties are not reliably obtained in practice at kilogram scale

Relevance to Energy and Efficiency in Manufacturing

- Thousands of clean energy applications for improved efficiency from heat exchangers, power lines to microelectronics
- Lightweight motors and wiring could save 15 lbs Cu per automobile
- $10B/year potential savings in high voltage aluminum cable transmission losses

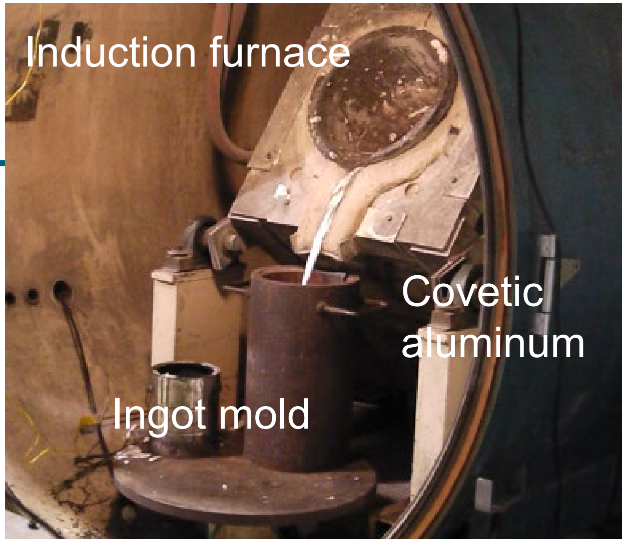
Goals/Objectives

- Understand fundamentals of how carbon is converted to graphene in liquid metal with applied current
- What are the process conditions under which electrical and thermal conductivities are improved?
- New knowledge → design improved system for reliable conversion

Why is this so hard to do?

- Requires new scientific understanding of the carbon nanophase formation
- Requires advanced microscopy, spectroscopy, C analysis methods
- Transforms non equilibrium metal + graphene structure to a stable structure (narrow parameter space)

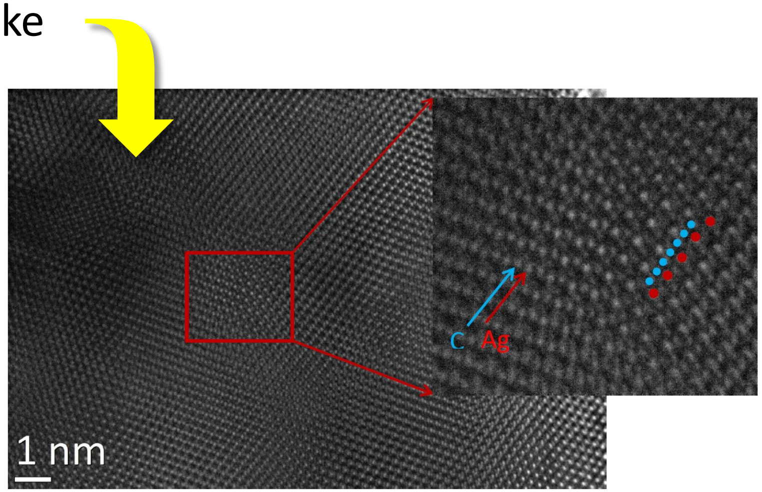
Technical Innovation



Current Practice

(e.g., U.S. Patent Publication No. 2017/0298476)

- Melt the metal, stir in carbon powder, apply current
- Thermal conductivity can improve up to 50%
- Electrical conductivity can increase up to 30%
- . . . Or the properties might get worse!! (that's the issue)
- A successful conversion yields a tenacious graphene-like nanophase that is strongly bound to the metal matrix



Atomic layers of Carbon are interlaced with metal matrix
(High resolution TEM image)

What's new? Back to basics. . .

- UMD conversion furnace has simplified geometries
- High level of control over all process parameters
- Will systematically vary the process according to design of experiments (some details are currently proprietary)
- Detailed microscopic and spectroscopic analysis
- End goal: design optimized conversion system for reliable conversions with consistent properties

Technical Innovation

Technology Impact

- Simple and cheap method of incorporating carbon nanostructures in metals
- Minimum increase in production counterweighed by reduction in losses in power transmission lines and cables/wires.
    - Lower fuel consumption
    - Higher current carrying capacity

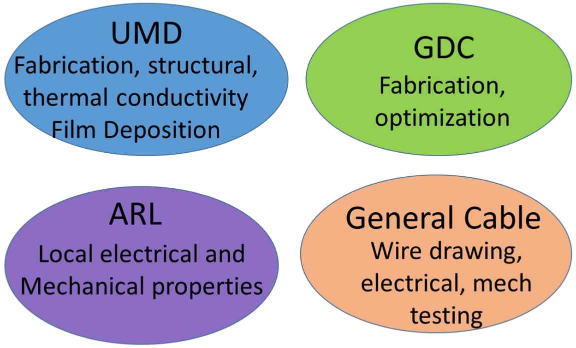
Simple Incorporation into Current Technology

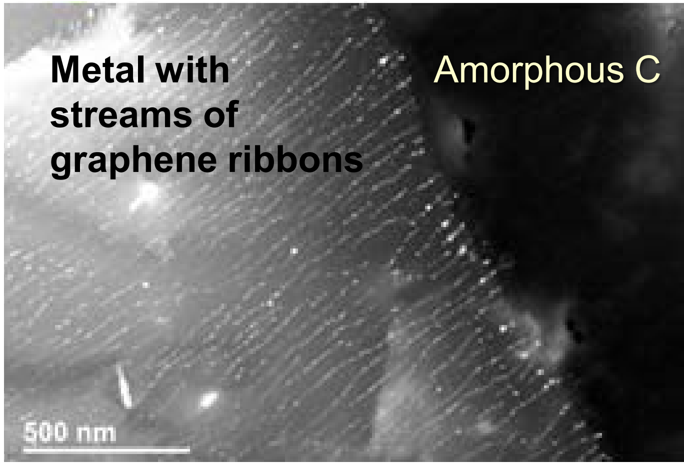
- UMD conversion furnace has simplified geometries
    - Allows control of different parameters for carbon incorporation
    - Can easily be incorporated for large scale manufacturing

Technical Approach

Identify the parameters that produce continuous network of nanocarbon in metals that give rise to increased electrical and thermal conductivities and tensile strength in nanocarbon metal composites of Al alloys and copper.

- Design and build reactor to physically model the process. -- UMD
  - Customized geometries of melt region and electrodes
  - Designs exploit numerical simulation results of the current and temperature distribution in the system using COMSOL
  - Perform conversions with different parameters, such as current distribution, temperature distribution, carbon level, conversion time, others
- Measure carbon content by XPS and Leco, carbon bond type by Raman scattering – UMD has state of the art instruments
- Characterize structure by XRD and TEM -- UMD
- Swage samples into rods -- external source
- Measure electrical conductivity and tensile strength of drawn wires -- General Cable (partner)
- Make samples into disks for thermal conductivity measurement -- UMD
- Measure local (micro/nano-scale) conductivity by c-AFM and local mechanical properties by nanoindentation by AFM –ARL (partner)
- Compare samples' properties with bulk samples made with kilogram scale commercial system – GDC (has commercial system)





Conversion of carbon into graphene was first imaged by U. Maryland

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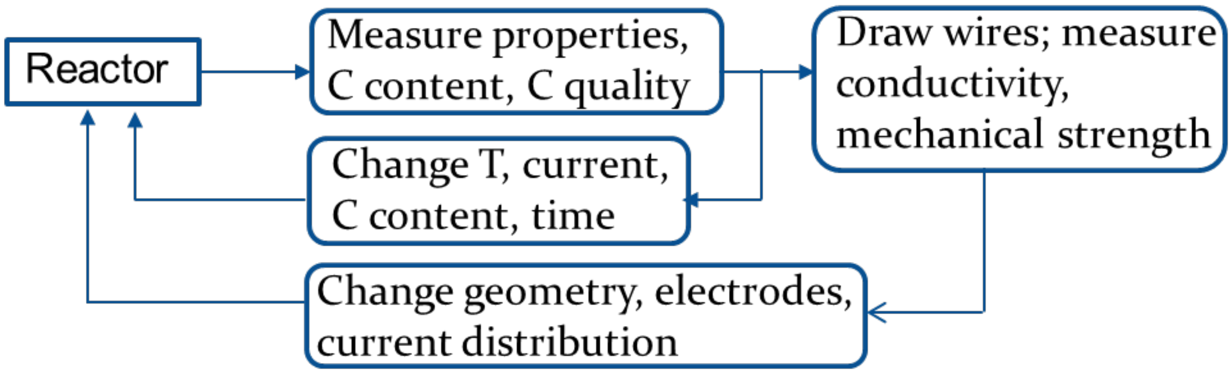

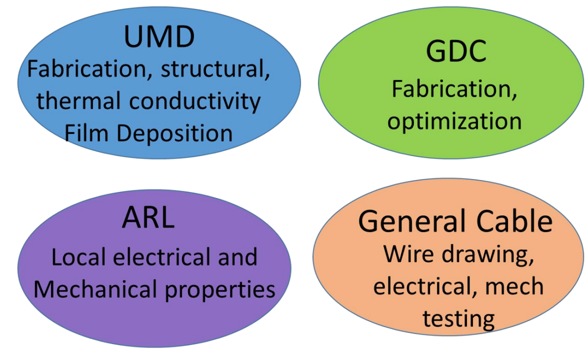

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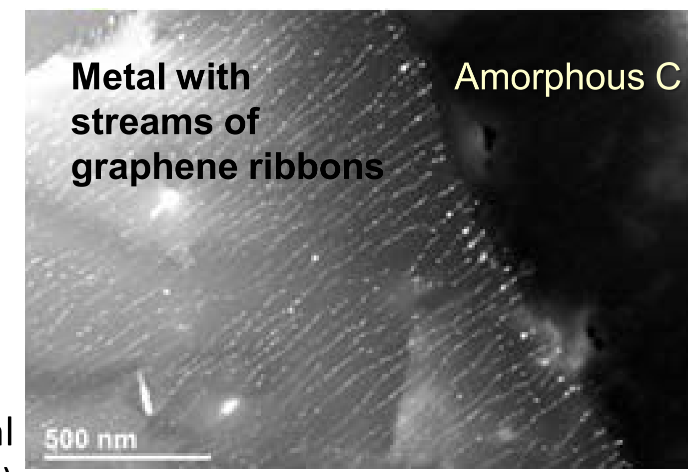

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Technical Approach

In addition, we will investigate covetic films by Pulsed Laser Deposition, sputtering, and e-beam deposition. . . and measure current carrying capacity --UMD

System Design and Optimization (BP2 and BP3)

- Use knowledge gained to design and build lab scale high throughput conversion system (~ 5 kilogram capacity or more)-- UMD, GDC
  - Model in COMSOL
- Synthesize covetics in new reactor, process to shape, characterize – UMD
  - Full battery of microscopy, spectroscopy, analytical characterization methods
  - Measure electrical, thermal and mechanical properties -- UMD, ARL and General Cable
- Design commercial-scale reactor for manufacturing – UMD, GDC, General Cable

Results and Accomplishments

Accomplishments

- Designed, built and tested several systems and electrode geometries at UMD.
- Currently testing different parameters to find optimum conditions for carbon incorporation that improve properties
- Analyzed samples by Raman spectroscopy, XPS, XRD, TEM, and measured electrical conductivity
  - Obtained Al 1350 with 4 wt % Carbon with 5 % higher conductivity than pure Al 1350
  - Conductivity increases with increasing nanocarbon crystallite size
- Measured local mechanical properties of Al 1350 with different Carbon content and local electrical conductivity (ARL)
- Small business collaborator (GDC) prepared larger samples of Al 1350 covetics for wire drawing, electrical conductivity and mechanical properties that are being tested by General Cable
- Published a paper on the mechanism of carbon conversion in the journal Carbon, and will submit another paper for publication soon.
- Presented results at MS&T, MRS Fall Meeting and two invited talks

Future Work and Milestones

BP1 Targets:

- Produce covetic Al 1350 with 10% increase in electrical conductivity and 30% increase in tensile strength.
- Produce covetic Cu with 10% increase in thermal conductivity and 30% increase in tensile strength
- Develop optimum process parameters for C conversion.

BP2:

- Complete the study on the effect of carbon composition
- Complete Film deposition
- Complete design of high throughput Gen 3 system

BP3:

- Build and test Gen 3 reactor
- Produce covetics with uniform C content and improved electrical, thermal and mechanical properties

Transition (beyond DOE assistance)

- Continue to work with industrial partners on issues likely to arise during scale-up
  - Homogeneity of the carbon phase
  - Microstructure of the carbon phase
- Continuous improvement of structure and thermophysical properties
- Potential incremental improvements due to incorporation of additional alloying elements.
- Once repeatable samples with high conductivity is achieved further scale-up of the high throughput reactor will be performed by GDC Industries LLC at its plant in Dayton, OH.
- General Cable, one of the largest power cable suppliers in America, has a signed Joint Development Agreement in place with GDC. The JDA contemplates production samples initially from GDC followed by implementation of a high throughput reactor at one of the General Cable rod production facilities under a license agreement.