Materials Solutions for Light-Weighting Automotive Wiring

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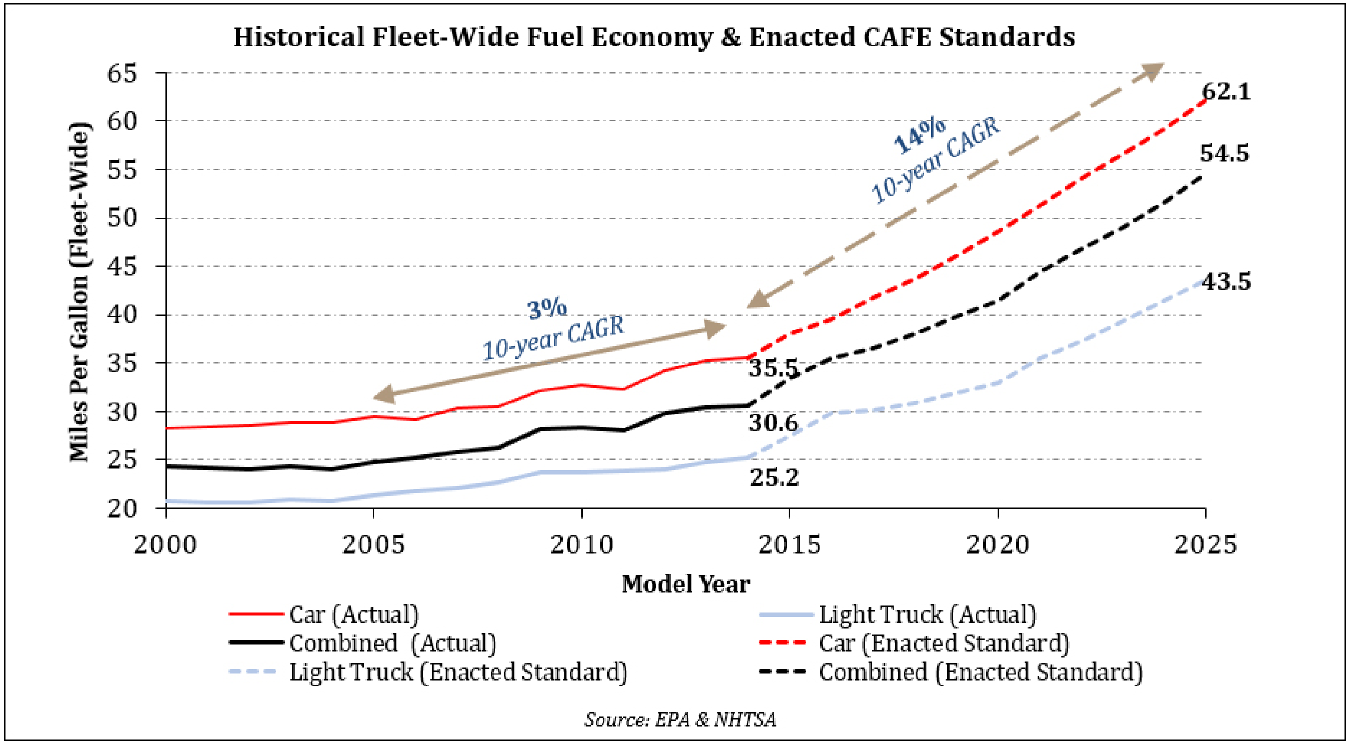
NANCY 2016

Improved Fuel Economy Standards



CAFE: Corporate Average Fuel Economy (production-weighed harmonic mean)

<u>Fuel economy standards improvement</u>

- Mandated by law
- Consumer demand
- Technology advancement

Improved Fuel Economy by Light-Weighting

Mid-Size Car – 3.0L-4V gas engine with variable intake cam timing

DRIVE CYCLE			EPA								European	
						FUEL ECONOMY BENEFIT						FE Benefit
			City FTP75 (mpg)	Highway HWFET (mpg)	Combined (mpg)	City FTP75 %	Highway HWFET %	Combined %	City Label (mpg)	Highway Label (mpg)	ECE (mpg)	%
		Baseline	22.9	36.9	27.6				18.3	26.4	17.6	
Weight Reduction	5%	Baseline Engine	23.3	37.3	28.0	1.4%	1.2%	1.3%	18.5	26.7	17.8	1.0%
	10%		23.6	37.8	28.4	2.9%	2.4%	2.7%	18.8	27.0	18.0	2.1%
	20%		24.3	38.7	29.2	5.8%	5.0%	5.6%	19.3	27.7	18.3	4.1%
	5%	Engine Downsized for Displacement	23.8	37.9	28.6	3.6%	2.7%	3.3%	18.9	27.1	18.3	4.0%
	10%		24.6	38.9	29.5	7.4%	5.4%	6.7%	19.5	27.8	19.0	7.9%
	20%		26.6	41.0	31.6	15.9%	11.3%	14.3%	21.0	29.3	20.6	16.9%

Ricardo, Inc. 2008

Simple Weight Reduction

- EPA Fuel Economy improved by >5% for 20% weight reduction

Weight Reduction with Engine Displacement Downsized to Baseline Performance

- EPA Fuel Economy improved by >11% for 20% weight reduction

More than 90 percent of automobile energy consumption and carbon emission occur during the vehicle's use phase, with the mining, production and manufacturing phases accounting for just 10 percent or less (http://www.drivealuminum.org)

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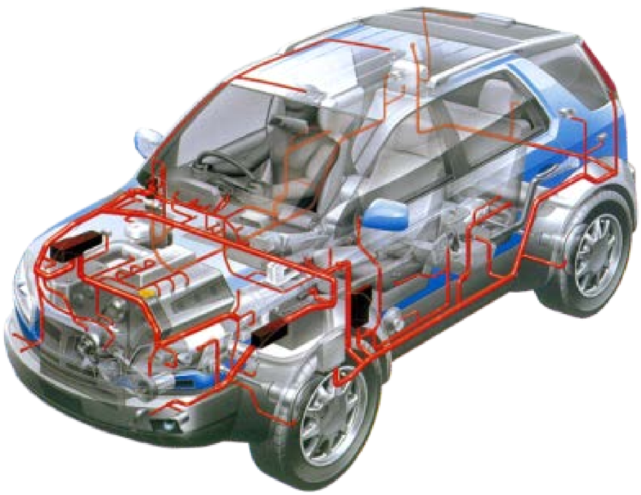
The Increasing Need for Wiring in Automobiles



Component Weight in a Passenger Car

1. Body Structure (300 kg)
2. Engine (150 kg)
3. Transmission (150 kg)
4. Wiring (60 kg, but increasing)

900k tons of Cu consumed annually

Amount of wiring is increasing steadily

1970s	cruise control, check engine, electronic fuel injection
1980s	antilock braking, climate control, heating and cooling of seats
1990s	active cruise control, CD changers, dynamic stability control, navigation systems, roll-stabilization system
2000s	blind spot warning systems, Bluetooth integration, Internet access, rearview cameras, traffic sign recognition

Although the contribution of a wire harness to a car's weight is small, it is increasing due to constantly added electronic features.

Thus, there is a need for light-weighting wires and cables.

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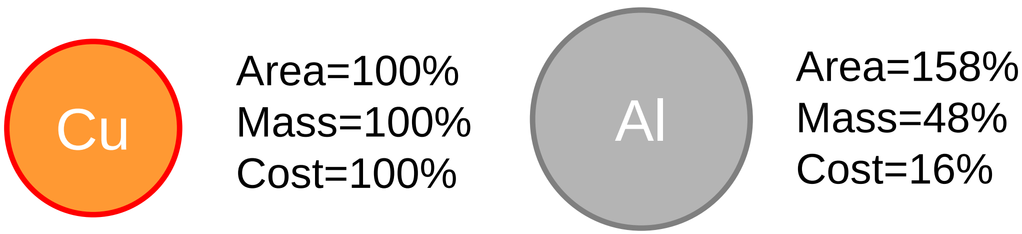
Why Aluminum ?

	Electrical Conductivity (10^4 S/cm)	Electrical Resistivity ($\mu\Omega\cdot$cm)	Density (g/cm^3)	Melting Point (°C)	Cost ($/lb) April 16
Copper	58.5	1.7	8.92	1085	2.14
Aluminum	36.9	2.7	2.7	660	0.69

<u>Cu and Al wires with same electric conductance</u>



- There can be a ~50% weight and ~80% cost reduction by switching from Cu to Al
- About 80% of automotive wiring can be made out of Al,
  20% are in hot areas such as the engine and require Cu to prevent softening
- Unlike other alternative technologies such as wireless there is no safety concern with Aluminum wiring
- Aluminum wiring poses some challenges (discussed below)

Recycling of Automobiles

www.aluminum.org

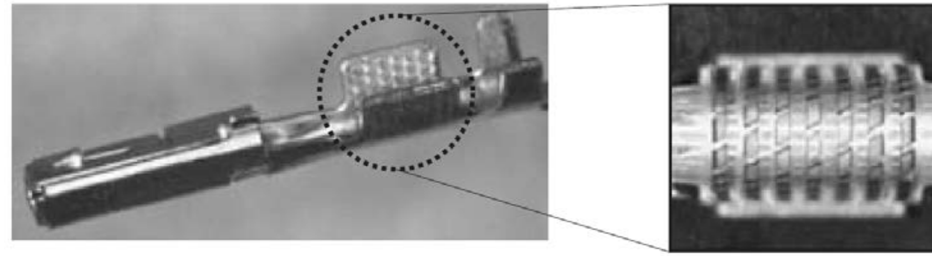
- Remelting Al uses only 5% of energy of producing new Aluminum from Al_2O_3 (*)
- 90% of automotive Al (~500k tons) recovered and recycled each year
- Recycling 1 ton of Al saves 21 barrels of oil
- Al residue is less detrimental than Cu residue to the mechanical properties of recycled Fe
- 345k tons of Al could replace 720k tons of copper, which is 80% of the amount used for the annual wire-harness production

Aluminum technology enables light-weighting and a less intense use of material thereby lowering the carbon footprint of both the manufacture and use of cars

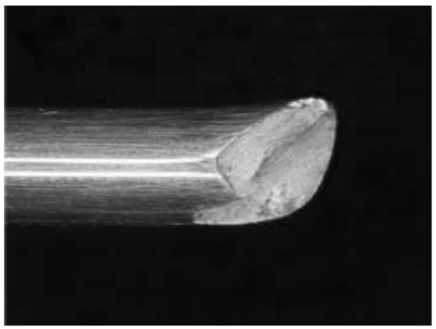
(*) S.K. Das et al, JOM 56, 14 (2004), JOM 59, 57 (2007)

Aluminum Technology Challenges

- Lower conductivity than Copper
- Low mechanical strength
- Corrosion when in contact with Cu
- Insulating Surface Oxide

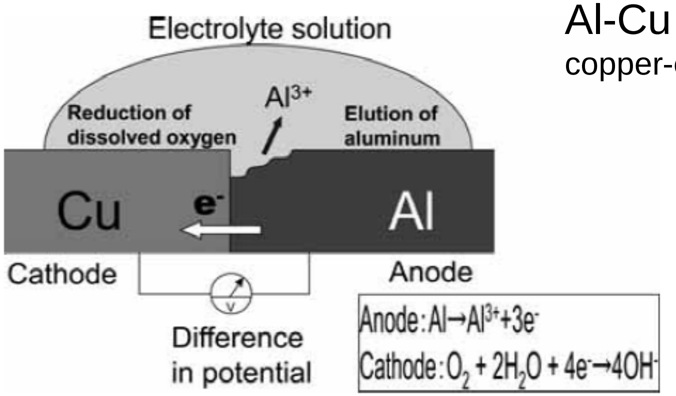


Serrated crimp to break Al-oxide



Broken Aluminum Wire

Corroded
Al-Cu contact
copper-electric.net



N. Nishimura et. al.
SEI Tech. Rev. 2014

	Copper	Aluminum	Effects on crimping
Surface oxide film	Cu_2O Conductivity 10 s/cm	Al_2O_3 Conductivity 10-7 S/cm ⇒ Insulating performance	Insulating oxide film ⇒ Increase in contact resistance
Conductivity (base material)	100%IACS	60%IACS	Increase in constriction resistance component
Coefficient of thermal expansion	$17.7 \times 10^{-6}/°C$	$23.6 \times 10^{-6}/°C$	Large variation in contact load relative to variation in temperature ⇒ Decrease in contact load, particularly on low temperature side

Y. Yamano et. Al. SEI
Tech. Rev. 2011

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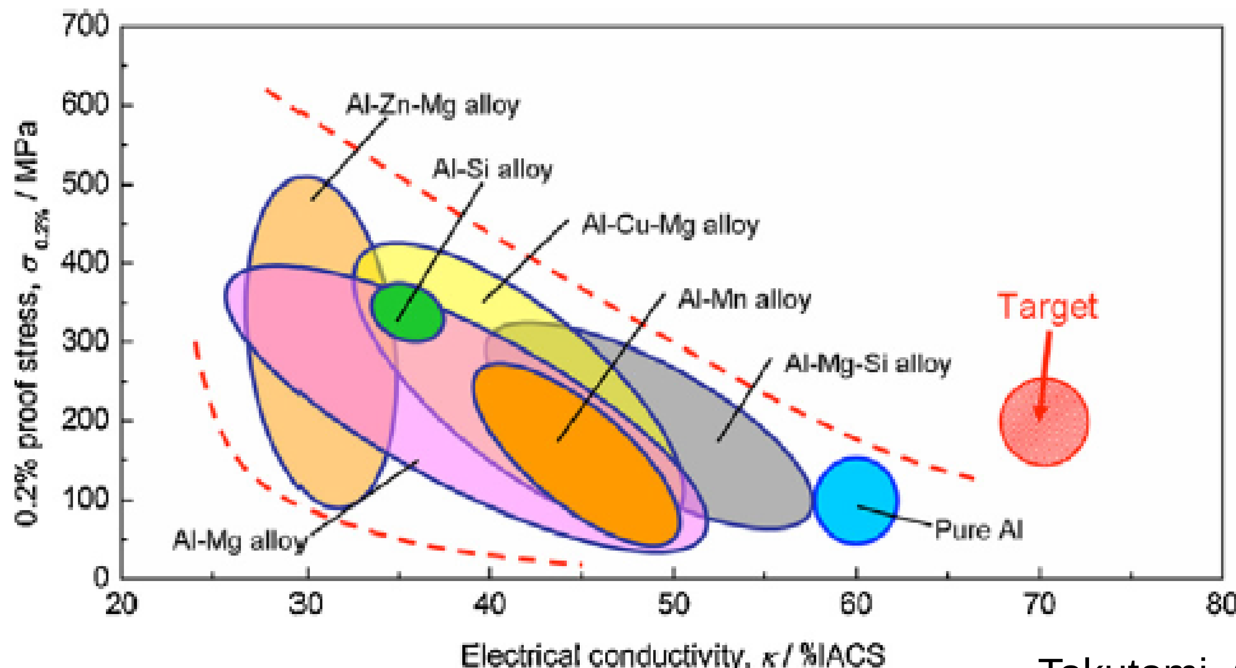
Mechanical and Electrical Properties of Aluminum Alloys



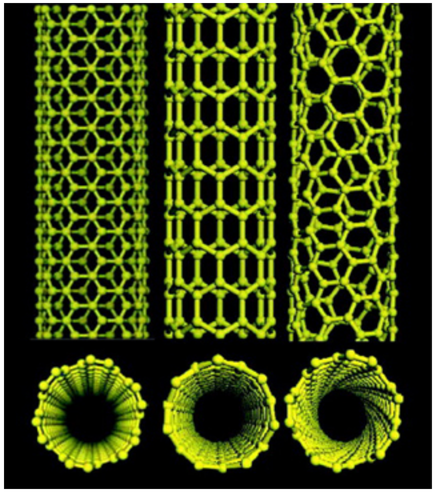
Tokutomi, CIRP Annals (2015)

The yield strength can be increased by alloying Al with other elements, however, the conductivity drops as a result of alloying

Carbon Nanotubes Properties

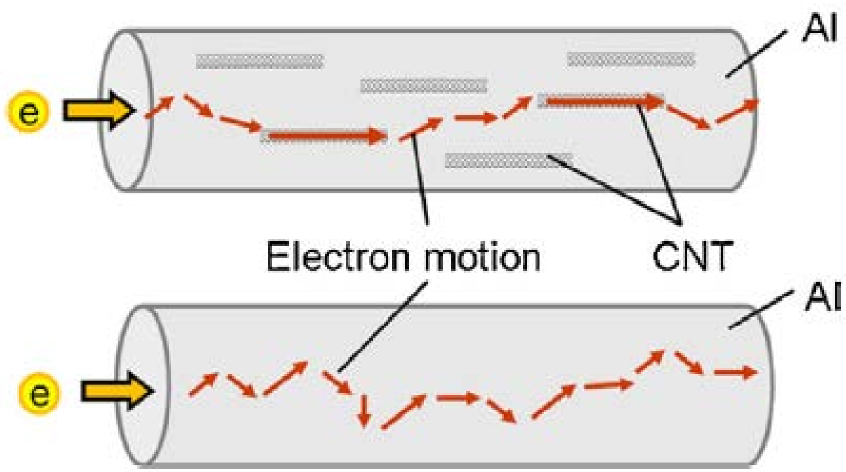
Material	Young's Modulus (GPa)	Tensile Strength (GPa)	Elongation at Break (%)	Electrical Conductivity (IACS)
CNT	1000	**10-150**	16-25	Semiconductor to metallic (varies)
Copper	117	0.2	16.6	1
Aluminum	69	0.1	23	0.62

- CNT *sp*^{2} carbon bond has the strongest tensile strength of any material known
- Depending on wrapping, CNT can be semiconducting (q=±1) or metallic (q=0); m-n=3p+q
- Very challenging to control CNT chiral structure
- Metallic CNT can carry 1,000x the current density of Cu



R.H. Baughman et al. Science (2002)

Aluminum - Carbon Nanotubes Wire Concept



<u>Al-CNT composite wire</u>
Diffusive and ballistic transport

<u>Al wire</u>
Diffusive transport

If metallic CNT can be aligned and percolated in the extrusion direction the electrical conductivity may be enhanced due to ballistic transport while achieving increased mechanical strength and reducing weight

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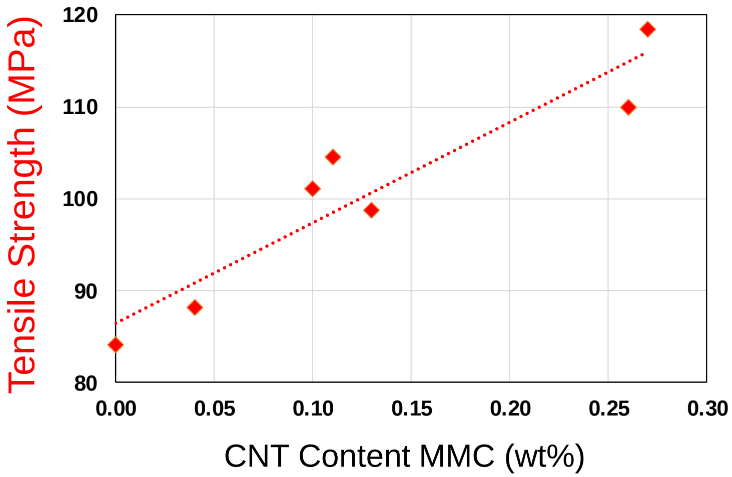
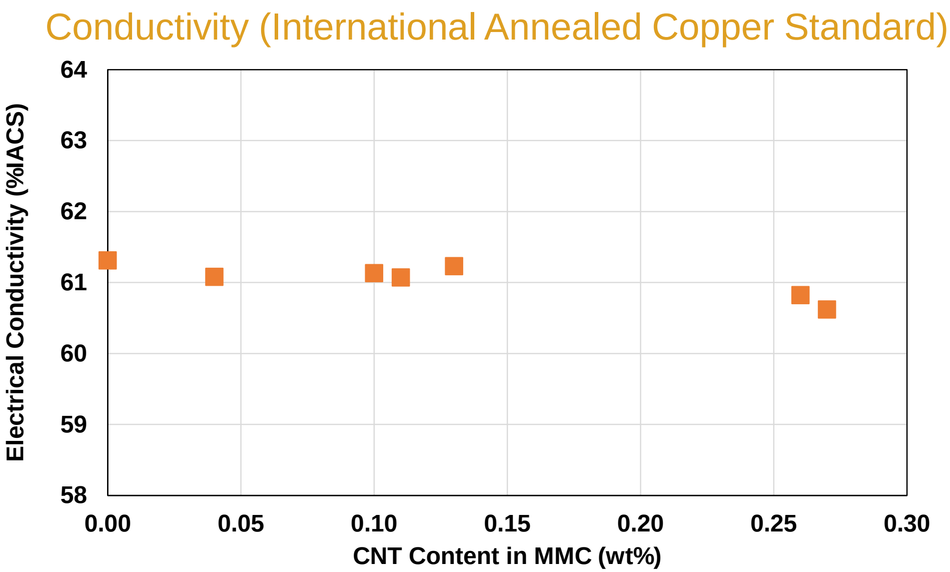
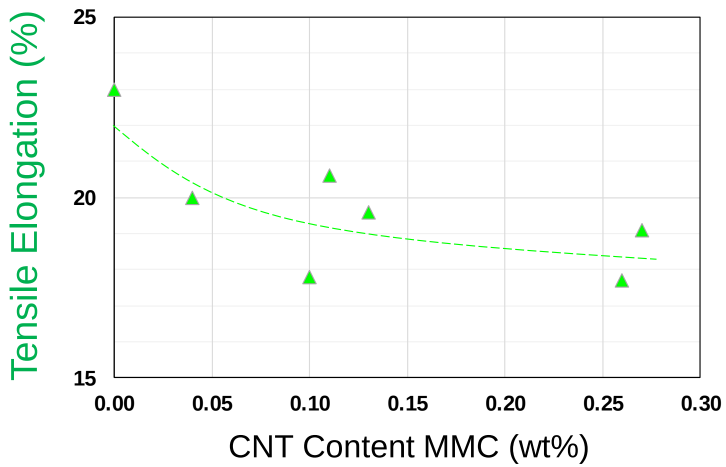
Mechanical Properties, Al-CNT 1.85mm Wire



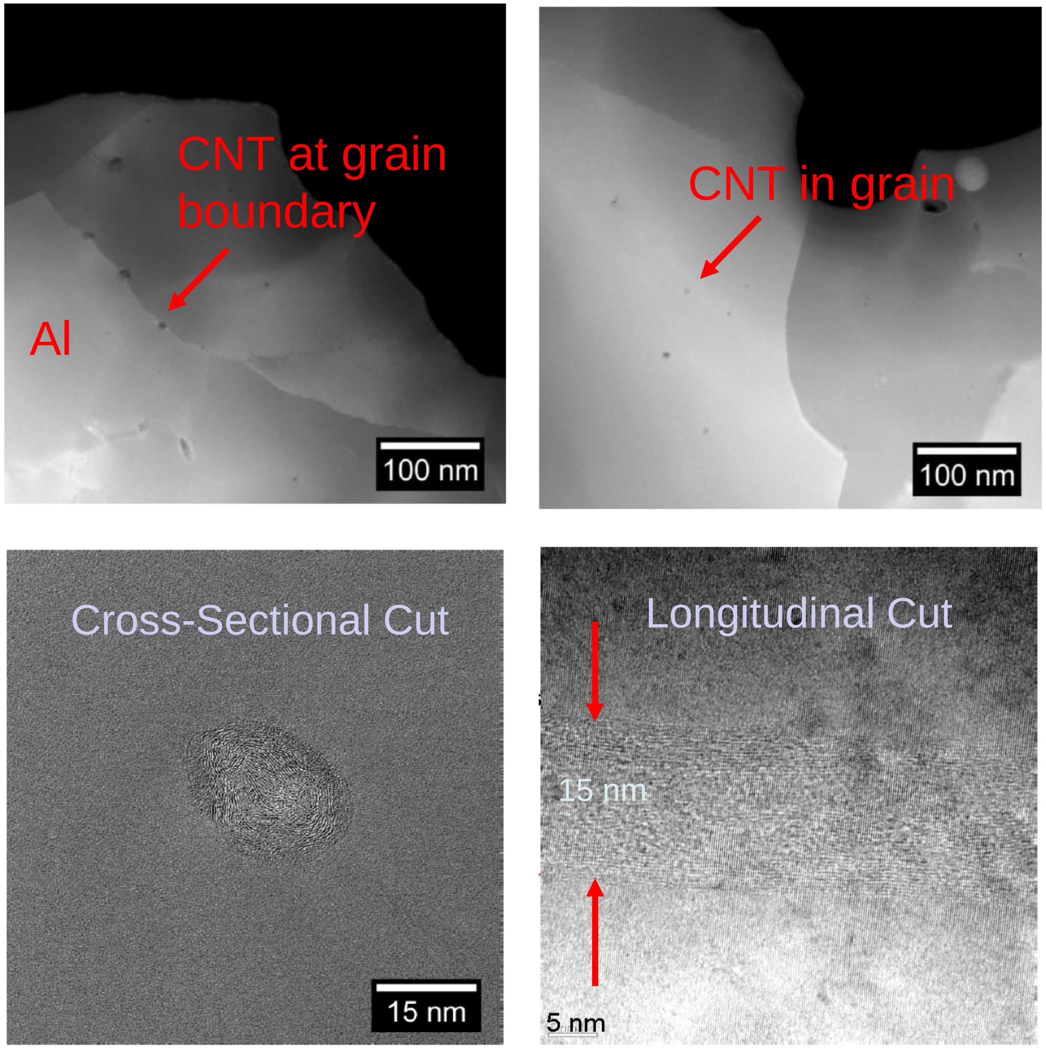




Large gain in tensile strength with only slight change in electrical properties

- Tensile Strength increases 40% with CNT content of only ~0.27wt%
- Elongation decreases with CNT content, but remains above 15% at ~0.27wt%
- Electrical conductivity remains largely unchanged up to ~0.27 wt% CNT

High Resolution TEM

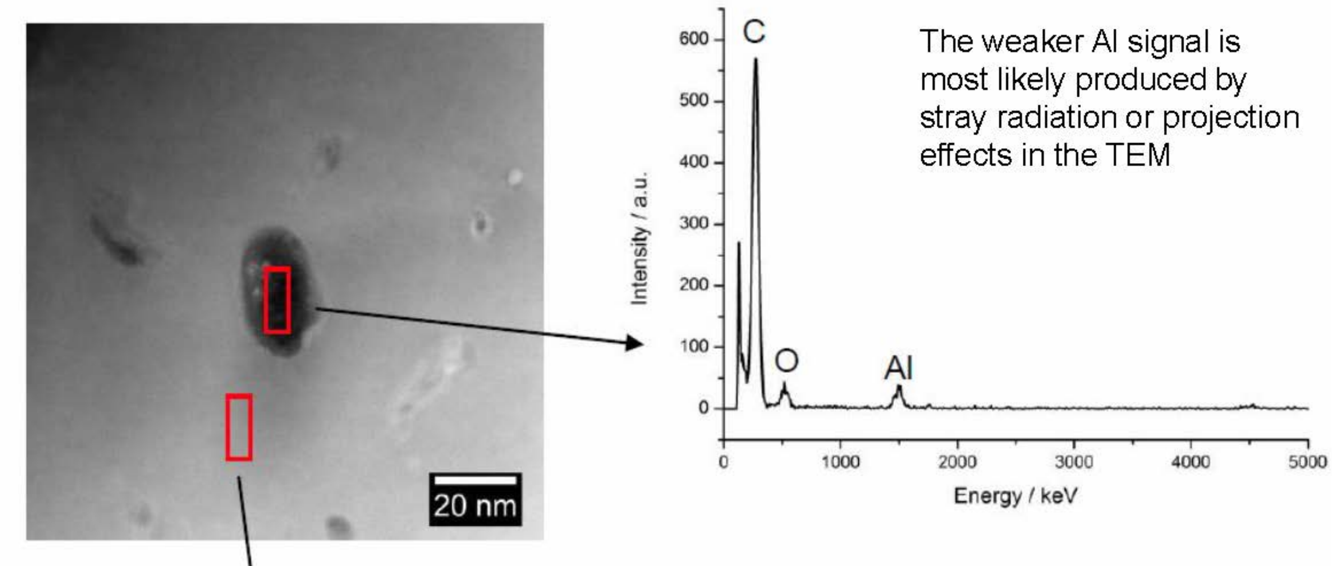


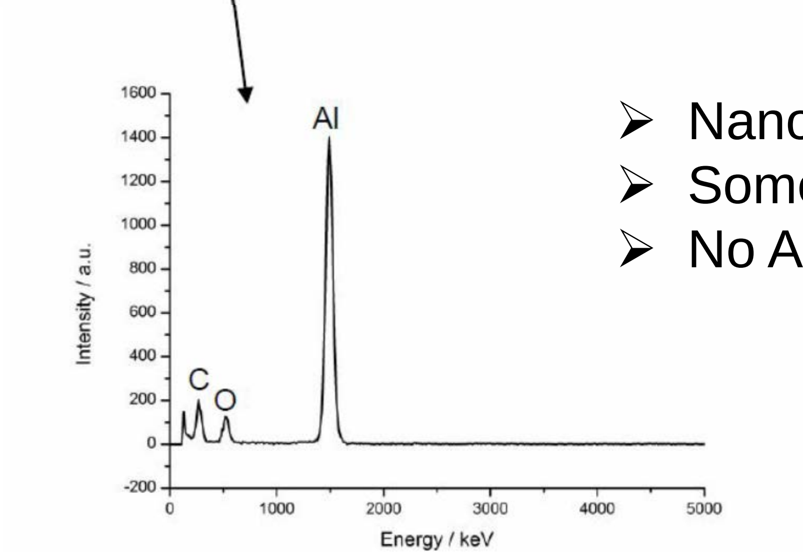
Nano-sized carbon particles are located

- at grain boundaries
- within Aluminum grains

- CNT strands are aligned with extrusion direction
- CNT is bundled as evident from large cross-section
- There is no CNT percolation
- Conductivity cannot be higher than that of Al without CNT percolation

EDX and HR-TEM of Al-CNT Wire



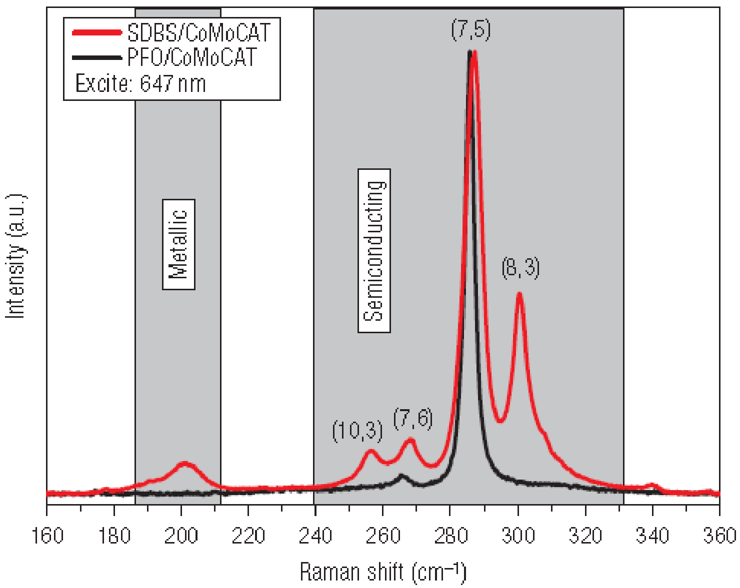


- Nano-sized particles are carbon material
- Some oxygen is found from extrusion process
- No Al-carbide interface is found

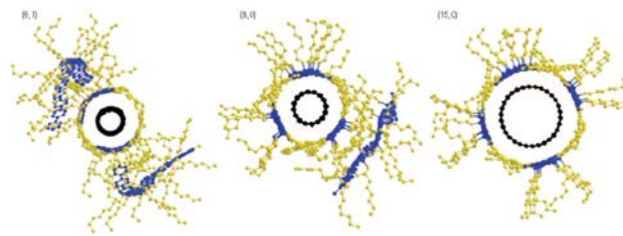
Separation of Semiconducting from Metallic CNT

Isolating metallic CNT for Al-CNT wires could improve conductivity

- Tagging of CNT by polymerization
- Isolation by centrifugation



A. Nish et al. Nature Publishing 2, 640 (2007)

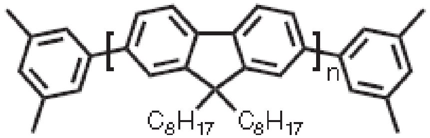


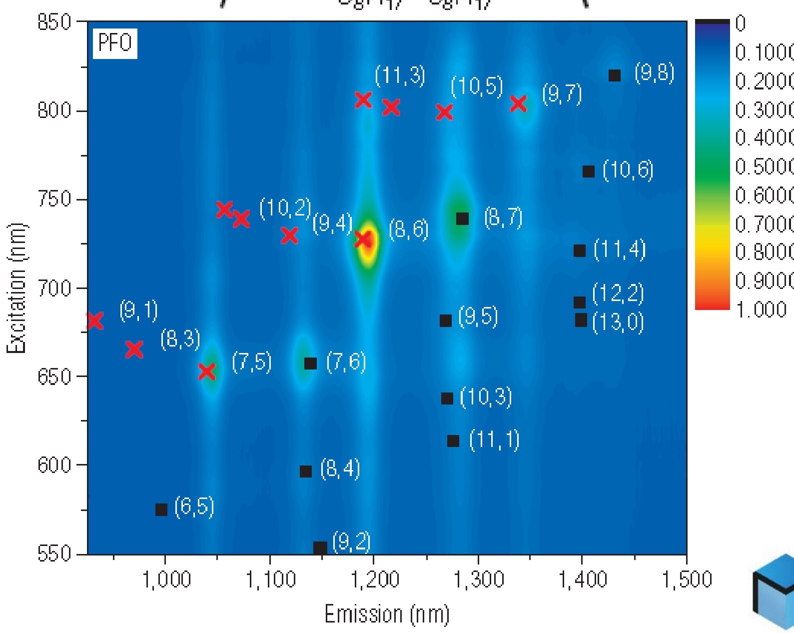
CNT

PFO Backbone

PFO Sidechains

PFO: Poly(9,9-dioctyl-fluorenyl-2,7-diyl)





Raman and photoluminescence shows selectivity towards semi-conducting CNT

Summary

- The weight of automotive components needs to decrease for improved fuel efficiency (driven by technology, consumer demand, and legislation)
- An automotive wire harness represents a small weight-percentage of a car, but due to increased connectivity its contribution is increasing
- Aluminum is light-weight and can be recycled indefinitely
- 345k tons of Aluminum can replace 720k tons of Copper for automotive wiring in the near future for lower weight and cost, saving on mining cost and green house gas emission
- Aluminum wiring technology faces several issues, including lower mechanical strength, electrical conductivity, and corrosion
- Light-weight Al-CNT composite wires with improved mechanical strength have been demonstrated
- Isolation of metallic CNT for Al-CNT wire may increase conductivity