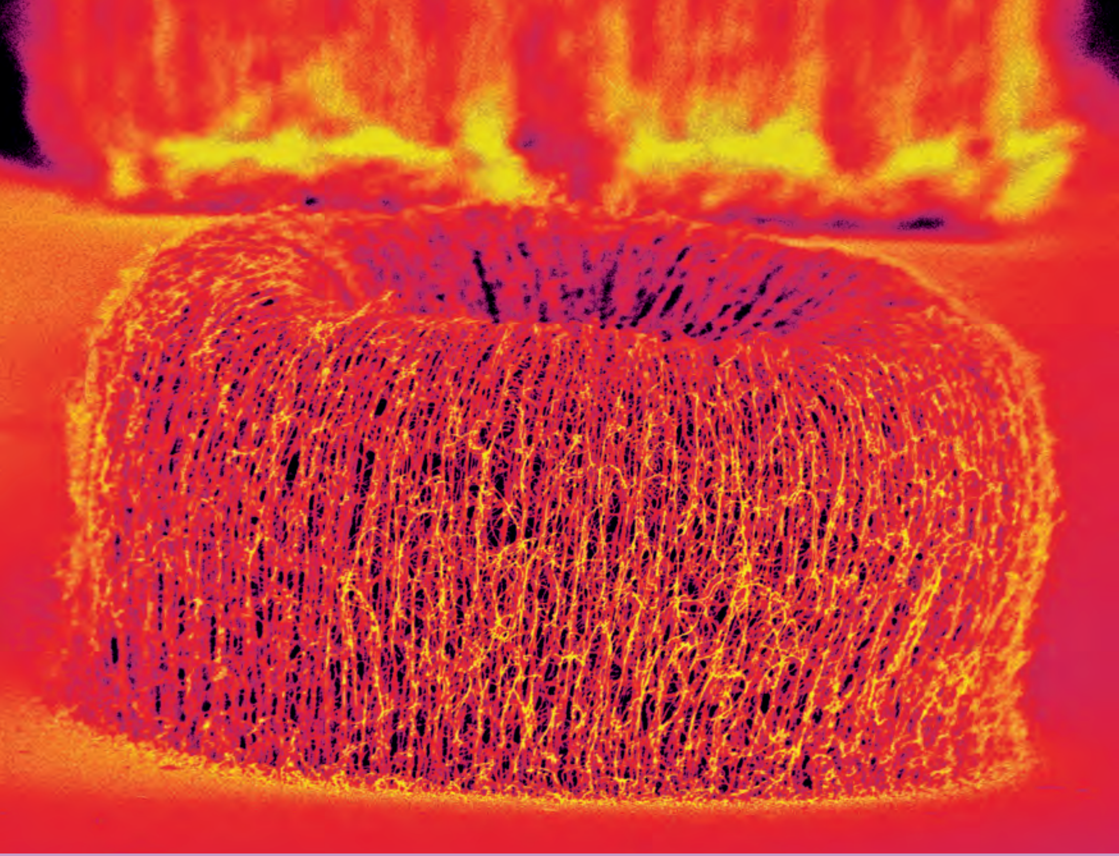


Advanced Nanotube Application and Manufacturing Initiative

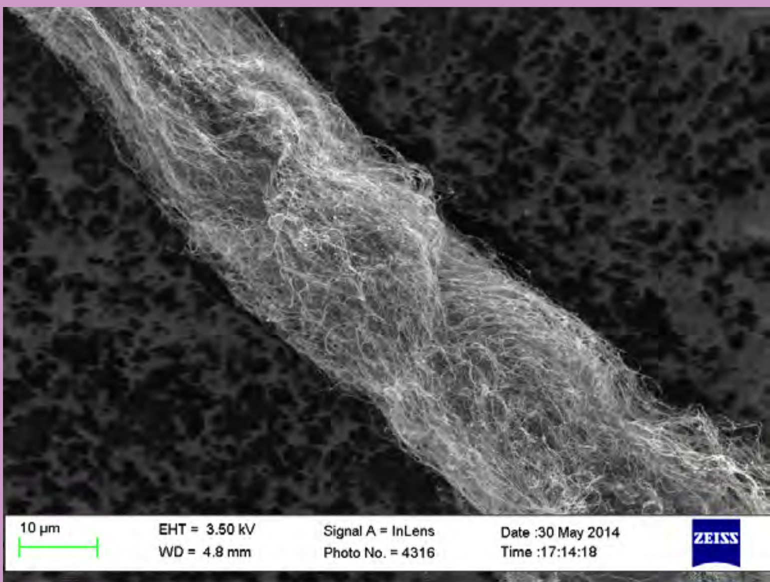
UNIVERSITY OF CAMBRIDGE

Carbon Nanotubes (CNTs) are proving one of the most exciting new materials being developed. As well as being as strong as Kevlar, they possess a wide variety of additional functionalities which show promise for applications for many diverse, commercial functions.

Converting the promise offered by CNTs into commercial reality remains a significant challenge and barrier to the industrial sector in realising the benefit of the past twenty years of academic study. This project directly addresses the industrial utilization of CNTs and seeks to close the gap between academic achievement and commercial return.

EPSRC has granted 2.8 million pounds to support this Initiative, and multiple million of other research grants are currently supporting fundamental studies of these materials. The academic investigators and participating industrial partners are seeking ambitious companies to join this Initiative. By working cooperatively the aim is to develop a new generation of disruptive CNT based products of global significance.

The science is complex but the methodology simple; the academic partners operating as an active bridge between CNT manufacturers and end use developers providing fundamental insight which will optimise raw material and end product design to produce maximum benefit.



Multifunctional CNTs for fibre and mat production

Cover Photograph: 'Cool Science is HOT' By Pola Goldberg Oppenhiemer of the University of Cambridge

ANAM Initiative

The Initiative will create a proving ground for the production and use of advanced functional CNT-based materials within prototypes specific to the industrial members. Unlike many research projects, the ANAM Initiative will focus on the end requirements of its industry collaborators, allowing flexibility of project choice and focus to be led by those partners and adapting to their changing needs throughout the project's lifespan. Building on academic research at the University of Cambridge and Ulster University, and with EPSRC funding of £2.8 million already awarded, the Initiative seeks to produce functional materials directly within continuous gas-phase processes, optimising CNT material quantity and quality, while controlling both physical and chemical functionality.

CNT Aerogel Formation

Initiative Structure

The Initiative will be organized into themes focusing on high throughput, advanced functionality and material applications. Industrial consortium input will lead the material applications theme in proposing CNT functional material projects, such as light-weight, electrical conductors for motors and high-surface area, high-activity catalysts, sensing structural light-weight body panels. Material requirements identified in these projects will serve as constraints to the optimization work within the high throughput and advanced functionality themes, focusing the plethora of possible directions to those of use to industry and, more specifically, to the Initiative's industry collaborators. As additional functionalities and properties of CNTs are discovered the industrial partners will be able to use the skills and expertise of the multi-disciplinary and experienced research team to take advantage of these developments, imparting greater functionality and value to future designs.

The high throughput theme will investigate methods of achieving increased production with focused efforts on scaling CNT hot-wall reactors to high-Reynolds number flow, as well as advancing new approaches via atmospheric plasma CNT systems. This theme will be guided by the applications identified by the industrial consortium to deliver materials fit for purpose to prototype development.

The advanced functionality theme will develop novel methods of imparting the functional behaviour required by the Initiative's industrial partner end-users. Initial efforts will seek to maximize inherent CNT anisotropic electrical and thermal conduction, specific strength and catalytically activated surface area phenomena. Advances in the physical and chemical nature of CNTs will be engineered by alignment of CNTs via charge-mediated gas-phase self-assembly procedures and new in-situ CVD coating processes.

CNTs – uses and applications

CNTs have been hailed as the wonder material of the 21st century with new scientific discoveries of properties and applications seemingly appearing daily. The ANAM Initiative seeks to harness

	CNT Mat/Fibre		Comparable Materials		
Specific Electrical Conductivity					
	S/m	S m-1 / (g cm-3)		S/m	S m-1 / (g cm-3)
Highest	6,700,000	19,600,000	Cu	59,000,000	6,584,821
Average	400,000	1,000,000			
Tensile Strength					
	GPa	GPa/SG		GPa	GPa/SG
Highest	1.50	1.50	Al	0.60	0.21
Average	0.50	0.50	Kevlar 49	2.20	0.40
Stiffness					
	GPa	GPa/SG	Steel	GPa	GPa/SG
Highest	150	150		200	25
Average	50	50			
Knotted Strength				**Kevlar 49**	**Carbon Fibre**
	Gpa/SG			Gpa/SG	GPa/SG
Unknotted	1.22		Unknotted	2.20	2.30
Knotted	1.20		Knotted	0.40	0.03
Surface Area				**Activated Charcol**	**13X Molecular Sieve**
	m2/g			m2/g	m2/g
Average	500		Average	500	750
Themal Conductivity				**Copper**	**Carbon Fibre**
	W/K/m			W/K/m	W/K/m
Average	1100		Average	483	180

CNT fibre knot

the potential of CNT properties for the commercial sector by developing prototypes specific to industrial collaboration partners, allowing them to focus on applications relevant to their industry sector and corporate needs.

CNTs have many possible uses; initially prized for being strong and lightweight, they are also highly electrically and thermally conductive. Additionally, they have a wide range of optical properties such as photoluminescence, near perfect black body optical absorption[1] and Raman scattering.

CNT Fibre (produced uniquely by one of our industrial collaborators) can be used to improve many of the functions where traditional carbon fibre is utilised. For example, with a better weight-to-strength ratio than steel[2], automobile manufacturers are considering incorporating CNTs into car panels and structural components.

Yet it is the additional, non-structural, functionalities that create the most exciting possibilities for the usage of CNTs, providing companies with the opportunities to incorporate supplementary functionalities within existing products; for example, adding sensing capabilities to structural applications or variable conductivity to current carrying applications.

Having higher specific conductivity than copper[3], aligned arrays of CNTs could replace many copper wiring applications with a fraction of the weight, e.g. creating light-weight motor windings. Replacing wiring in aircraft offers considerable weight reduction and thus fuel savings. Ultimately the goal, which is considered achievable, would be to reduce loss on power transmission grids by replacing aluminium based conductors. Aerospace manufacturers are seeking to use thin coatings of CNTs to dissipate static charge, replacing copper mesh. In addition to a weight saving of 9:1 CNTs have yet another advantage over the traditional copper; they can be configured to self-diagnose damage. With CNTs, the damage could be diagnosed by

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[1] Vertically aligned ‘forests’ of CNTs can have absorbance of 0.98–0.99 from the far-ultraviolet (200 nm) to far-infrared (200 μm)

[2] CNT 150 GPa/SG; Steel 25 GPa/SG

[3] CNT 19,600,000 S m-1 / (g cm-3); Copper 6,584,821 S m-1 / (g cm-3

monitoring the conductivity of the film, allowing the airline to decrease downtime and thus both save time and money. This damage diagnosis in structural and semi-structural automotive applications has the potential to unlock restrictive insurance requirements.

With anisotropic thermal conductivity, CNTs can be used to dissipate unwanted heat from microprocessors. This function is already being exploited in prototype applications; CNTs allow the processor chip to remain cool even with prolonged use and embedded in wearable fabrics.

The high surface area of CNTs permits substantial opportunities for usage in liquid and gas filtration membranes, particularly those with enhanced catalytic functions and for small particles and molecules where Brownian motion is the dominant mass transfer mechanism.

The electrical conductivity and strength properties of knotted CNTs gives rise to the possibilities of making electrical connections merely by tying together strands of CNTs, avoiding the need for costly joining processes in electrical components and reducing the risk of damage to the component.

The EMI shielding properties of CNTs, particularly when incorporated as part of a composite material, are being developed in applications such as mobile phones, space programs and aviation, and also in civil engineering projects, where CNTs are integrated in to the fabric of the building to create a fully shielded built environment.

Among the other uses of CNTs are novel solar cells, rechargeable batteries, biosensors, radar-absorbing coatings, anti-fouling paint and ultra-capacitors.

Within the ANAM Initiative, the specific applications to be developed to prototype will be tailored to the requirements of the industrial collaboration partners.

Synthesis

The Cambridge method of CNT synthesis is unique, creating continuous production of CNTs, rather than the traditional batch process utilised by other systems. A gaseous source of carbon, hydrogen and catalysts containing iron and sulphur, such as ferrocene and thiophene, are injected in to a tube furnace. Nanoparticles of iron form, while the sulphur conditions their surface. In the hot zone, typically between 1100-1300^{o}C, the carbon source is catalytically decomposed. Once the carbon reaches its solubility limit, carbon is precipitated forming an aerogel of nanotubes, or nanotube smoke, which is elastic. This aerogel can be captured by continuous collection from the reaction zone and wound out of the tube in fibre form. The uncondensed aerogel can also be collected as sheets, forming a nanotube film.

Initiative Research Team

In order to scale up functionalized material production specific to end-use applications, CNT synthesis must be controlled at the nano-, micro-, and macro-scales. Accordingly, the research team consists of a multidisciplinary group from the University of Cambridge with expertise in the fields of engineering, including fluid dynamics, reacting flows, gas-phase chemistry, nanomanufacturing and gas-phase assembly; and material science, including CNT material synthesis and characterization and reaction modelling. Ulster University researchers contribute significant expertise in plasma nanomaterial synthesis. The combined proficiency of the research team offers the unique experimental and modelling capabilities from nano- to macro-scales necessary to achieve physical and chemical CNT functionality.

Brief Resumés of Principal Academics

Alan Windle

Alan Windle is Emeritus Professor of Materials Science in the Department of Materials Science and Metallurgy. His research team is based around the creation and exploitation of carbon nanostructures in materials science. He was closely involved in the founding of Cambridge Molecular Design, a materials software company, and of the Melville Laboratory for Polymer Synthesis at Cambridge. Professor Windle is Director and CSO of Q-Flo, a company designed to exploit the spinning of carbon nanotubes into fibre directly from the reaction zone at 1250°C.

Adam Boies

Adam Boies is a Lecturer in the Energy, Fluid Mechanics and Turbomachinery Engineering Division at the University of Cambridge. His research focuses on characterizing the evolution, dynamics and impacts of gas-phase nanoparticles and gaseous pollutants. His laboratory activities include experimental studies in the area of gas-phase particle measurement with applications in emissions monitoring. Key elements of this work include nano-catalyst synthesis in collaboration with Johnson Matthey to develop materials for robust use at high temperatures. Recent work has also focused on carbon nanotube synthesis techniques in collaboration with Q-Flo and Tortech which are seeking to commercialize large scale carbon nanotube production.

Paul Maguire

Paul Maguire is Professor of Plasmas and Nanofabrication at NIBEC Nanotechnology & Integrated Bio-Engineering Centre and School of Engineering Ulster University. His main research interests lie in the development and integration of microplasma, microfluidic and microfabrication techniques for application in industrial nanomaterials, biocompatible nanomaterials coatings, 3rd generation PV solar cells, clinical and environmental sensors devices. He has many years' experience in materials synthesis, deposition and etching especially with group IV (e.g. tetragonal amorphous carbon, carbon nanotubes) and groups II-IV materials. His current focus includes two EPSRC funded projects on real-time bacterial pathogen detection and nanoparticles for 3rd generation solar devices; nanomaterials for electronic devices volume manufacture and Deep-Ocean Lab-on-Chip, in collaboration with Scripps Institute of Oceanography and NUI-Galway.

Davide Mariotti Dr Davide Mariotti has international experience in US, Japan and UK working within academia, government research institutes and with industry (e.g. Applied Materials-USA, MKS Instruments-USA, Caterpillar/Perkins Engineer-UK). He is now Reader in Plasma Science and Nanoscale Engineering at the Nanotechnology & Integrated Bio-Engineering Centre-NIBEC at the Ulster University and he is a recognised international leader in Plasma Nanoscience (e.g. EU-COST Action TD1208). His research focuses on the synthesis and processing of nanoscale materials with custom-built advanced atmospheric pressure plasma technologies. Current funded projects from a range of sources (e.g. EPSRC, FP7, Leverhulme Trust etc.) include for instance scaling-up nanomaterial fabrication and third generation photovoltaics. His plasma research has a broad spectrum of potential applications from materials processing to applications in bacteria detection.

Simone Hochgreb Simone Hochgreb is Professor in experimental reacting flows in the Department of Engineering at the University of Cambridge. Her research interests are on reacting flows, including autoignition, pollutant formation and combustion instabilities. She has developed optical techniques for measurements of species, velocities and nanoparticles in engines, flames and gas turbine combustors, sponsored by a number of agencies and companies in the USA and the UK. Her current interests are in non-intrusive laser measurement techniques for temperature, species and velocities.

Michael De Volder Michael De Volder is a Lecturer in the Institute of Manufacturing at the University of Cambridge. He studied nanoparticle synthesis and assembly in some of the world leading groups at MIT, University of Michigan and Harvard, and he now leads the NanoManufacturing group in the department of Engineering at the University of Cambridge. He also worked for several years at IMEC, an industry funded microelectronics research institute before becoming a Lecturer. His current research interest include hierarchical assembly of nanoparticles and scale-up of their manufacturing processes. He is recipient of an ERC starting grant in this field.

James Elliott James Elliott is a Reader in Macromolecular Materials at the Department of Materials Science and Metallurgy in the University of Cambridge, with over 10 years' experience of studying polymeric and polymer nanocomposite materials. His most recent work focuses on the optimization of mechanical, electrical and thermal properties of carbon nanotube fibres, and modelling of carbon nanotube synthesis in collaboration with Q-Flo and Tortech. He was a Japan Society for Promotion of Science (JSPS) Invitation Fellow and Visiting Professor at the University of Tokyo in 2008, where he led a collaborative project on modelling processes to control of chiral angle in nanotube synthesis by floating catalyst method.

Matthew P. Juniper Dr Matthew P. Juniper is a Reader in the Department of Engineering at the University of Cambridge. He studied Natural Sciences and Engineering at the University of Cambridge and received his M.S and PhD from the Ecole Centrale de Paris. After a period as a consultant at McKinsey & Co., he joined the University of Cambridge as a lecturer and fellow of Trinity College. His research interests are in the broad area of fluid mechanics. They are: reacting flows, flow stability, mixing, suppression or generation of turbulence, adjoint-based numerical methods for optimization of flow geometry. He has worked with companies on a variety of projects relevant to the ANAM Initiative including identifying the instabilities and their control in both a gas turbine fuel injector and a cyclonic separator; designing a low pressure, high mixing, off-gas burner for a methane-powered fuel cell; generating mono-dispersed (same sized) droplets with an ultrasonic droplet generator .

Norman Fleck Norman Fleck is Professor of Mechanics of Materials in the Department of Engineering at the University of Cambridge and Founder Director of the Cambridge Centre of Micromechanics. He hold many honours and awards, including Fellowships of the Royal Society and of the Royal Academy of Engineering. His research interests include the role of microstructural evolution during processing and use upon material performance; sintering of thermal barrier coatings; the dependence of toughness and erosion resistance upon the morphology of microstructure; the mechanics of failure of lattice materials under extreme environments.

Industrial Collaboration

A key part of the Initiative is the inclusion of an industrial consortium of manufacturers seeking to utilize functional materials, as well as UK-based CNT technology companies. The industrial consortium will have a vital and pro-active role in the project, steering and focusing the research to provide solutions and applications specific to their individual company needs. Over the term of the project, it is expected that each industrial partner is directly involved in specific project streams conducted by post-doctoral research associates that relate directly to their interests. The industrial partners will be encouraged to provide on-going input to develop and expand the directions of the project.

As a proving ground for CNT production and use, the Initiative will provide support for prototype development and seek to expand the use of multi-functional CNT materials.

It is envisaged that the consortium of companies selected to create the industrial partnership team will form a non-competitive group, enabling the intellectual property resulting from the Initiative to be shared equitably amongst the collaborators.

CNT collection

A bulk CNT synthesis company, Q-Flo (CNT fibre and mat producers), will be included in the Initiative. TorTech NanoFibers, licensing Q-Flo technology, will provide pilot-scale production for purposes of prototype development. Dry CNT fibre and mat will be further processed at the University of Cambridge for prototype development.

Manufacturers seeking to employ CNT fibre and mat within their products will serve as the centre for prototype development.

Members supporting the Initiative due to the recognized advantages of advanced-functional CNT material use include, aerospace, catalyst, chemical sensing, defence and automotive industries.

Project and Finance

The ANAM Initiative is jointly funded by an EPSRC Manufacturing Advanced Functional Materials research grant of £2.8 million over 5 years commencing in July 2015 and by contributions from the network of industrial collaborators.

Members of the industrial consortium will be asked to contribute £15,000 per year over the 5 year term of the Initiative and will, in turn, receive generous intellectual property (IP) rights. Further contributions will allow for direct allocation of PhD students to projects of interest for the contributing member. In-kind contributions would also be welcomed from industrial partners; these could be stand-alone or in addition to membership of the consortium. The Universities will retain publication rights to the research.

Funding within the Initiative will be used at a minimum to employ postdoctoral research associates (5 PDRAs), and students (5 PhDs and 10 Masters) supported by industry and departmental contributions. PhD student projects will focus on long-term high throughput and functionalization goals to develop process models and conduct experiments. PDRA research will develop material applications where projects will be linked with industrial collaborators for prototype development and validation.

An industrial research liaison officer will facilitate knowledge transfer within the consortium. The Initiative advisory board, comprised of 2 of the industrial partners, 2 of the academics and 2 external experts, will review projects annually, selecting among project proposals from academic and industrial members. The lead of the Initiative will rotate on an annual basis, ensuring equity in the selection of projects and allocation resources.

Join the consortium

In the first instance, potential industrial members of the Initiative should contact Dr. Adam Boies for a further information on the project.

For further information, please contact

Dr. Adam Boies
amb223@cam.ac.uk
01223 746 972

Alexandra Bolton
ahb34@cam.ac.uk
01223 332 834

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