

MPC NEWSLETTER

Issue 5 - Spring 2006

The Newsletter of The Materials Performance Centre



**Driving Innovative
Ideas for the NDA**

**Materials Modelling
in the MPC**

**Nuclear Specialists
Meet at Manchester**

**Research
Opportunities
with the MPC**

DR DANUT STEFANESCU

The work of Dr Danut Stefanescu, post-doctoral research fellow in the Materials Performance Centre, has recently been recognised by two awards. The first of these was the 2004 Professional Engineering Publishing Award for his article in the *Journal of Strain Analysis for Engineering Design* entitled "Elastic Strains around Cracked Cold-Expanded Fastener Holes Measured using the Synchrotron Diffraction Technique". The second was the 2004 Central Electricity Generating Board Prize for his article in the same journal entitled "Measurement and Prediction of Fatigue Crack Growth from Cold Expanded Holes".

Dr Stefanescu has been working in the field of residual stress for many years and is interested in research in areas such as the measurement of residual stress in components, using different diffraction and mechanical strain release techniques; the treatment of residual stress in modelling of fatigue behaviour of components; and the development of experimental techniques for residual stress measurement.

In his current role for the MPC he continues to work in this field, using lab X-ray diffraction, Raman spectroscopy, electron laser speckle pattern interferometry, image correlation, beach

marking techniques and materials characterization techniques such as scanning electron microscopy and electron back scatter diffraction. He has worked in the area of short fatigue crack nucleation and propagation is currently working on the effect of residual stresses on ferritic steels toughness.

At the time of going to press, Dr. Stefanescu had begun a new job at Airbus. All at the MPC congratulate him on his recent achievements and wish him every success in his future career.



SUMMER INTERNSHIPS

Internships offer the chance to engage in real research in a high quality, lively and friendly environment. Students receive competitive remuneration for working on industrially relevant projects using state-of-the-art facilities.

A number of summer internships are available for 2006 in the Materials Performance Centre. Applications are welcome from pre- or post- final year science and engineering students. Interns will carry out short research projects for approximately 10-12 weeks. A list of the projects and an applications form is available on our website, www.materials.manchester.ac.uk/mpc.

Generous studentships of £1,000 will be awarded to two interns to cover living expenses and assistance to find accommodation during the internship will be provided. Please contact Dr João Quinta Da Fonseca (joao.fonseca@manchester.ac.uk or 0161 306 8959) if you would like further information or an informal chat about any of these opportunities.

The closing date for the studentships is 15 April 2006.

THE DIRECTOR'S CUT

Welcome to the Spring 2006 edition of the MPC Newsletter. This year began with a number of positive events for the Materials Performance Centre. We continued our collaboration with the EDF with a student recently starting work on the modelling of flow-assisted corrosion, and with additional funding in place for an additional student to work on the mechanism of stress corrosion cracking of Alloy 600 in PWR environments. Informal meetings have been held in Manchester and EDF, les Renardières to discuss additional projects. We hosted a successful day of focus group meetings to discuss the future of intermediate level waste last month and this is reported further on page 7. We took part in an Open Day at the University to promote the work of the MPC and its relevance and importance as a stimulating career for tomorrow's budding researchers. This was a great success and is reported on page 7.

The New Year brought a series of welcomes and farewells for the MPC. We said a fond farewell to two of our researchers, Dr Paul Wood and Mr Frederic Wacogne who left us for exciting new opportunities in industry. We wish them every success in their future careers. We warmly welcome our new researchers into the team, Tony Cook, Abdulla Al-Shatter, Elsie Onumonu, Rob Burrows, Anissa Amimer, John Francis, Kerry Taylor, and Anthony Horn. The article on page 6 gives more insight into the nature of the research they will be conducting with the MPC. <Andrew will also be saying something about the new collaboration with British Energy: Colin English et al> In our Winter 05 edition, we promised an overview of the work of Professor Philip Withers in the area of residual stress. We present this in the article on page 7 which focuses on his Directorship of The Unit for Stress and Damage Characterisation in the School of Materials here at the University of Manchester. Finally, we are pleased to be able to announce a range of opportunities for people wishing to work with the MPC. A number of internships are outlined above and our PhD and PDRA opportunities are advertised on the back page. We have further information on all our opportunities on our website

(www.materials.manchester.ac.uk/MPC) and welcome all applications. We hope you enjoy this edition of the Newsletter.

Professor Andrew Sherry
Director, Materials Performance Centre



MATERIALS MODELLING IN THE MPC

Materials performance in the nuclear industry is particularly difficult to understand and predict. Materials are used in a wide range of unique operating conditions: high temperatures, steep temperature gradients, corrosive environments and intense radiation fields often over extended timescales. Nuclear power reactors can have service lives of over 40 years and during the subsequent decommissioning, materials performance needs to be predicted over 100s if not 1000s of years. This is compounded by the difficulty in testing and inspecting material during both service and decommissioning. In this context, it is clear how computational modelling of materials has become an indispensable tool for the safe running of power plants and safe management of waste.

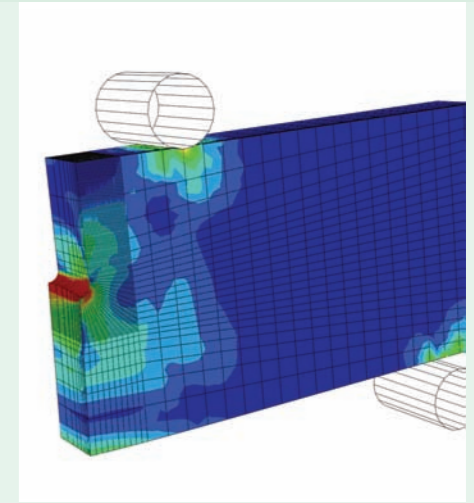
This is reflected in the research activity of the Materials Performance Centre, where modelling plays a key role in the research of almost all aspects of material performance. This involves both the extension of the modelling approaches currently in use and the development of new multiscale, multi-physics models, supported by research in fundamental computational modelling. These new models will replace current (mostly) empirical models, which cannot be used outside the current range of experience. By incorporating the mechanisms responsible for material behaviour, future models will be more amenable to extrapolation. This is particularly important where plant-specific materials are unavailable, where the loading of plant components cannot be directly measured and when new classes of material and (or) manufacturing processes are being considered.

Structural integrity of metal components is one of the areas of computational modelling research plays a major role. Prof Andrew Sherry and visiting scientist Dr Martin Goldthorpe are running a number of research projects looking at crack propagation in residual stress fields and different constraints, looking at the influence of second phase particles and material history on their fracture resistance. In collaboration with Dr João Fonseca, these models are being further developed to include effects of crystal

plasticity and multi-scale deformation heterogeneity associated with it. These will lead to the development of more accurate, less conservative failure predictions that will allow reactors to run safely for longer. This research benefits from close collaborations with both SERCO Assurance and Nexia Solutions.

Modelling is also being used to understand the mechanisms controlling corrosion. Dr Nick Stevens is working on systems where electrochemical effects determine the behaviour of corroding boundaries, looking into the interactions between these effects and other environmental factors. Such a situation occurs in Flow Assisted Corrosion, where accelerated mass transport effects can cause localised corrosion rates to far exceed those that would be expected. Corrosion combines with fracture mechanics to give stress corrosion cracking (SCC), a very important but poorly understood failure mechanism. SCC is the subject of another ongoing modelling project. Dr Stevens' interest in is the application of percolation theory to crack growth. This project is a collaboration with Dr James Marrow and Dr Andrey Jivkov. It looks at how strain distributions in 3D structures guide a percolating crack front. This project has allowed simulations to be created to explore the interaction of grain boundary cracking resistance on crack bridging to be explored. It is supported by Rolls Royce Marine PLC.

In a large number of operative and recently decommissioned reactors, it is the properties of graphite that define the reactors life. Graphite research is an important area in the MPC's portfolio with a strong focus on computational modelling. Prof Barry Marsden's work in the continuum modelling of graphite core behaviour provides a valuable insight into the evolution of internal stress within the core during life. Calculations are based on a constitutive law, which incorporates the highly non-linear irradiated graphite property changes, irradiation creep and various interactions. Within the model, the total strain is described as a function of elastic strain, primary and secondary creep strain, thermal strain, and strain due to irradiation-induced dimensional changes. Some of the property changes observed in graphite during service have origin in a change in porosity content and character. Dr Alex Fok, in collaboration with Dr Paul Mummery and Dr James Marrow, has



been developing models for this process using new ways of modelling real microstructures characterised by tomography and local properties determined by nanoindentation.

All of these activities are underpinned by fundamental computational modelling, an activity led by Dr Andrew Willets, a senior research fellow in the MPC. Fundamental computational modelling is able to address detailed questions of these materials at an atomic scale. The insight that is gained is then either used directly or incorporated into models at successively larger scales to answer more complex questions. Currently we are looking at two different approaches to describing corrosion and diffusion processes. The first is molecular dynamics, which is being used to look at diffusion in mixed metal oxide spinel structures. The second is kinetic Monte Carlo, where the evolution of materials is predicted using information from molecular dynamics.

Supported by the state of the art material characterisation facilities available at the School of Materials, which provide essential validation and model inputs, modelling plays an important role in the MPC and it is a growing activity. The next step is towards supercomputing, with the set up of a multi-node computational cluster. It will allow us to run larger, more detailed models to help unravel the mysteries of material behaviour in the most demanding operating conditions.

FOND FAREWELL TO FORMER RESEARCHERS

We say a fond farewell to Dr Paul Wood, a former post-doctoral research fellow in the MPC and Mr Frederic Wacogne, who recently undertook a research project in the MPC. Both have recently successfully secured posts in industry. Paul has taken a position at

Oceaneering, Aberdeen as the Corrosion Engineer assigned to the Kittiwake offshore platform to carry out corrosion mitigation and integrity management. Frederic has taken a position at Nexia Solutions, Cumbria as an Operations and Technical Support Assistant in the Materials

Sampling and Inspection Team within the Materials and Products Resource Group.

The MPC wishes them both every success in their future careers.

DRIVING INNOVATIVE IDEAS

The core activities within the Materials Performance Centre are funded by the Nuclear Decommissioning Authority (NDA). The NDA is taking a long term view of the clean-up and decommissioning of nuclear sites. A better understanding of the behaviour of a range of materials in nuclear environments, including stainless

steel and graphite, will help in suggesting innovative new ideas to constantly improve their strategic thinking. It is through the development and application of these ideas that both time and budget will be saved.

Based at The University of Manchester, the MPC is well positioned to both develop

Mechanism and Prediction of Stress Corrosion of Zirconium in Nitric Acid

Paul Harrigan
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Previous work has shown that zirconium may be subject to stress corrosion cracking in nitric acid and this project has been studying the mechanism of the cracking process. It appears that the stress corrosion cracking is associated with a form of transpassivity, and consequently the major effort has been concerned with developing an understanding of the mechanism of the transpassivity and the factors that might influence it. A number of

experiments have been performed in order to test various hypotheses about the transpassive behaviour; no clear mechanism has been identified, although a number of possibilities have been excluded, including a role of nitrite or fluoride species. On the basis of the experiments it seems unlikely that stress corrosion cracking will be observed in the relatively low acid concentrations used in reprocessing.

Electrochemical Cleaning of Metallic Structures

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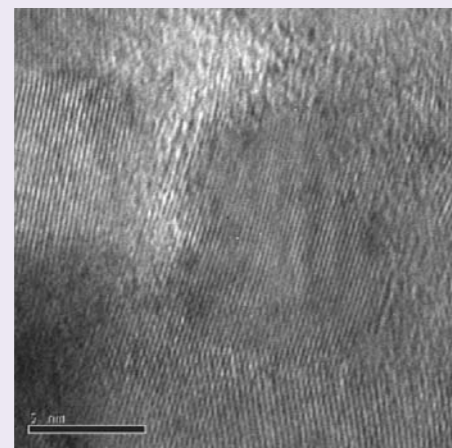
The contamination of equipment used to move and store active materials in fuel storage ponds, known as 'pond furniture', is undesirable as the movement of such equipment between generation and reprocessing facilities spreads the contamination through the chain of

transport equipment and to the receiving ponds. Techniques for the measurement of Cs contamination have been developed, and work on decontamination using chelating species and electrochemical activation is set to commence in the second year of the project.

Irradiation Damage in Graphite Crystal Structures

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Dr James Marrow
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High resolution transmission electron microscopy, nano-indentation and Raman spectroscopy have been applied to the study of low temperature irradiation damage in nuclear graphites. Neutron irradiation has been simulated using argon ion bombardment and electron beam irradiation. Raman spectroscopy is sensitive to irradiation damage and study of the effects of annealing of irradiated structures is being used to understand the kinetics of Wigner energy release. This is of relevance to

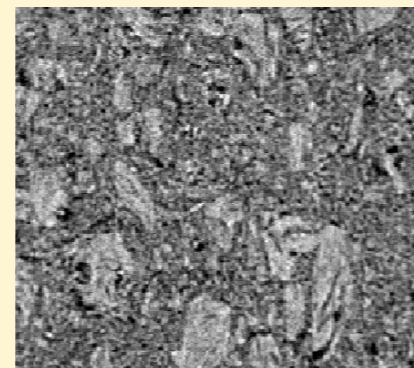
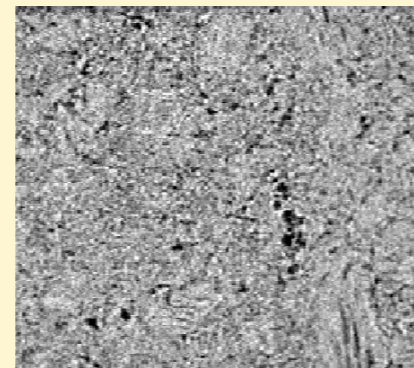


the disposal of nuclear graphites in cemented grouts, for which knowledge of the rate of heat generation by Wigner energy release is essential.

creative new ideas in materials research and maintain a strong knowledge base in this area. This is accomplished through a number of focussed PhD and postdoctoral projects, as described below.

Microstructure/Property Relationships in Nuclear Graphite

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Dr Paul Mummery
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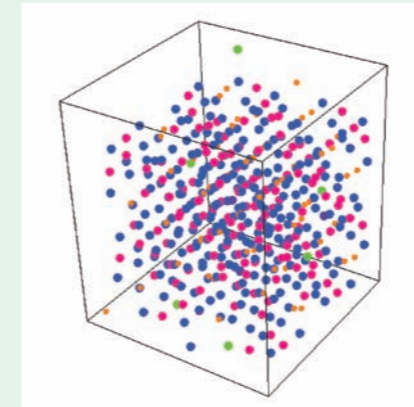
X-ray tomography has been developed as a tool for density mapping in nuclear graphites, enabling three dimensional study of the distribution of porosity. The typical microstructure of graphite before and after oxidation is shown in the images to the right. The observed pore distributions are an input to analytical models for structure dependent transport properties, including thermal diffusivity, elastic modulus and strength. The technique has been verified using thermally oxidised graphites. If applied to radiolytically oxidised graphites, it would enable the non-destructive assessment of graphite structure and properties. This would be a significant contribution to the safe decommissioning of graphite moderator cores.

FOR THE NDA

Atomistic Modelling of Corrosion

Stephen O'Toole
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This project aims to gain a mechanistic understanding of the fundamental processes involved in key aspects of both the degradation of stainless steels, such as general corrosion and stress corrosion cracking, and contamination. Diffusion is an essential mechanism in all these processes and many more; the underlying focus of this project is in identifying the mechanisms and rates of diffusion in representative mixed oxide model systems containing iron, chromium and other elements used in steels. Currently, a combination of molecular dynamics and kinetic Monte Carlo simulations are being employed to study these mechanisms. Below is a snapshot taken from a molecular dynamics simulation looking at the diffusion of oxygen through a spinel structure.



Defects in Proton-irradiated Materials

Jonathan Duff (j.duff@postgrad.manchester.ac.uk)

The relationships between grain boundary structure, the development of irradiation damage and stress corrosion cracking are being studied in austenitic stainless steel. Proton irradiation is being used to simulate neutron irradiation, providing samples that can be observed in a non-active laboratory. The nature of the defects and the effects of irradiation on grain boundary segregation are being examined using high resolution electron microscopy. The image below shows stress corrosion cracking which occurred during testing of a proton-irradiated sample. The project aims to understand the microstructure parameters which indicate susceptibility to irradiation assisted stress corrosion cracking, in which irradiation damage during service can significantly influence the integrity of structures. This is of relevance to the safe decommissioning and long-term storage of reactor core internals.



Cement Electrochemistry

Evrpidis Tsaousoglou (e.tsaousoglou@postgrad.manchester.ac.uk)

The encapsulation of Mg and Al waste in cement is accompanied by an initial rapid corrosion of the metal accompanied by hydrogen evolution before a sufficiently thick layer of corrosion product builds up to slow the corrosion processes down. This rapid evolution of hydrogen can pressurise waste containers and raises safety issues. The use of Electrical Impedance Spectroscopy to investigate the corrosion process and

characterise both the resistance of the cement and the thickness of the corrosion layer offers a non-destructive route to investigate the aging processes in the wasteform. We have been lucky enough to be allocated beamtime on the Tomography beam line at the Swiss Light Source in early March, which will enable us to image the metal/cement interface and measure the volume of the voids formed during the initial cement setting phase.

Mechanistic Investigation of Internal Corrosion in Nuclear Waste

Elsie Onumonu (elsie.onumonu@postgrad.manchester.ac.uk)

Intermediate Level Nuclear Waste, (which can be metallic, oxides or mixtures of types of materials) is encapsulated in cement and stored in 500 litre 316L Stainless Steel drums in various forms defined by NIREX.

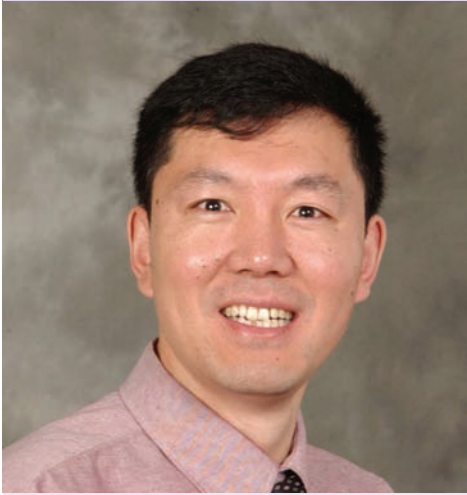
The cement environment is normally protective towards steel of all types due to the high internal pH, but aggressive ions can promote local corrosion on the interior of the drum. The effects of the active waste in emitting both radiation and heat can increase the corrosivity of the aqueous solution within the cemented wasteform. The drum is expected to maintain its mechanical strength and prevent the release of material for a period of at least 500 years.

Our investigations will link in with work at Nexia and Magnox Electrical Ltd, where aged specimens prepared over the past 15 years have been prepared, and to study accelerating factors that might lead to premature corrosion and loss of integrity.



Intermediate Level Waste Grouted Drum.
Courtesy of Nexia Solutions.

We are also conducting research which aims to understand the mechanism of stress corrosion cracking and hence to simulate it under differing physical and chemical conditions. Initially this has involved simulating both anion and cation diffusion in mixed metal oxides, which are defected structures, and eventually the simulations will include the influence of grain boundaries. Modelling results will be compared with experimental TEM results and this work will be extended to look at oxide formation and the effects of stress. Our future modelling projects will include: H and He embrittlement of metals, improved interatomic potential development, decontamination modelling, large scale simulation and waste product modelling. For more information on this research, please contact Dr Andrew Willets (andrew.willets@manchester.ac.uk or 0161 306 4868).

SPOTLIGHT ON...
DR PING XIAO

Dr Ping Xiao is an associate scientist in the Materials Performance Centre and Reader in Materials Chemistry at The University of Manchester. He has developed an exhaustive research programme on both the fabrication and characterisation of ceramic coatings for nuclear fuel development, turbine blade protection and combustion engine component protection.

Dr Xiao is well known for his research into ceramic coating research, particularly on thermal barrier coatings (TBCs) which are being used for the protection of turbine blades in aero-engines and combustion chambers in the power generation industry. He has pioneered the development of impedance spectroscopy for non-destructive evaluation of TBCs and used impedance spectroscopy to determine the degradation and failure of TBCs after being exposed to high temperature environment. Dr. Xiao's group has developed a novel technique which can be used to fabricate TBCs and coatings for corrosion and erosion protection. His patent is being exploited by a consortium including 7 industrial companies and his group with support of a £1.2 million grant from the DTI and industry.

His research within the MPC includes development of fluidised bed chemical vapour deposition to fabricate multilayer Pyron C and SiC coatings on nuclear fuel particles, a key technology for the next generation of nuclear reactors. The research involves manufacture, characterisation and performance testing of coated particles and is carried out in close collaboration with Nexia Solutions at Springfield, UK. Dr Xiao said, "The establishment of the MPC gives me many opportunities to extend my expertise in coating research. The new project on coated fuel particles has presented me with many challenges. Our research will contribute to an international effort to develop nuclear energy for future applications, and promote the MPC's profile in nuclear science and engineering research".

CONFERENCE WATCH

See below for our selection of forthcoming events.

ASST 2006: 4th International Symposium on Aluminium Surface Science & Technology (ASST IV)

Beaune, France, 14 - 18 May 2006
More details can be found at www.asst2006.com

9th International Fatigue Congress (Fatigue 2006)

Atlanta, Georgia, USA, 14 - 19 May 2006
More details can be found at www.fatigue2006.com

Embedded Topical Meeting/2006 ANS Annual Meeting: Nuclear Fuels and Structural Materials for the Next Generation Nuclear Reactors

Reno, Nevada, USA, 4 - 8 June 2006
More details can be found at www.ans.org/meetings/docs/2006/nfsmngnr06-cfp.pdf

16th European Conference of Fracture (ECF16)

Alexandroupolis, Greece, 3 - 7 July 2006
More details can be found at <http://ecf16.civil.duth.gr>

The International Carbon Conference (Carbon 2006)

Aberdeen, Scotland, UK, 16 - 21 July 2006
More details can be found at www.carbon2006.org

ASME/PVP 2006/ICPVT -11 Conference

Vancouver, Canada, 23 - 27 July 2006
More details can be found at www.asmeconferences.org/PVP06

57th Annual Meeting of the International Society of Electrochemistry

Edinburgh, UK, 27 August - 1 September 2006
More details can be found at www.fontismedia.com/ise_events/ise06_annual/index.php

7th European Conference on Residual Stresses (ECRS 7)

Berlin, Germany, 13 - 15 September 2006
More details can be found at www.ecrs7.de

International Conference on Crack Paths (CP 2006)

Parma, Italy, 14 - 16 September 2006
More details can be found at www.mvcongressi.it/CP2006/conf-info.html

MMM 2006: Third International Conference on Multiscale Materials Modeling

Freiburg, Germany, 18 - 22 September 2006
More details can be found at www.mmm2006.org

The 3rd International Conference on Recrystallisation and Grain Growth (ReX and GG III)

Jeju Island, Korea, 10 - 15 June 2007
More details can be found at www.rex-gg-2007.org

International Conference on Experimental Mechanics: Experimental Analysis of Nano and Engineering Materials and Structures (ICEM 13)

Alexandroupolis, Greece, 1 - 6 July 2007
More details can be found at <http://icem13.gr>

WELCOME TO NEW RESEARCHERS

We are pleased to welcome a number of new researchers to the MPC at both PDRA and PhD level. In the corrosion area, Tony Cook has recently arrived from New Zealand. He will be the PDRA working on the new EPSRC Keeping the Nuclear Option Open programme which is focussing on the influence of irradiation and atmosphere on the EAC behaviour of stainless materials. He is joined by Abdulla Al-Shatter who is funded by BNFL to undertake a PhD addressing irradiation effects on EAC. Elsie Onumonu recently started her PhD which is supported through the University to address internal corrosion of intermediate level waste in cement. This programme will draw on experimental results obtained over many years at BNFL. Finally, we are delighted that Rob Burrows (BNFL Magnox Generation) is able to continue his external PhD on Magnox pond corrosion. We are also looking

forward to our first EdF-funded PhD student, Anissa Amimer who will be developing computer modelling approaches of corrosion.

In the structural integrity area research is focussing on residual stresses and their influence on fracture. John Francis has joined us from Australia. As a PDRA, he will be developing computer simulation techniques of the welding process. Kerry Taylor has commenced her Rolls-Royce funded on the influence of residual stresses on ductile cracks. Finally, we are delighted to welcome Anthony Horn (Corus) who has just commenced an external PhD on the performance of real defects in service.

If you would like any information regarding these research projects, please contact Dr Jane Deakin (jane.deakin@manchester.ac.uk or 0161 306 4840).

NUCLEAR SPECIALISTS MEET AT MANCHESTER



A group of scientists and engineers from across the UK nuclear industry met at Manchester on Tuesday, 14 February to discuss the technical issues surrounding Intermediate Level Waste (ILW) and the management of spent nuclear fuel. The meeting, which was chaired by Prof Andrew Sherry of the Materials Performance Centre, was attended by Dr James McKinney the NDA's ILW strategy manager and Dr Paul Gilchrist, NDA strategy manager for nuclear materials and fuel. Representatives from the United Kingdom Atomic Energy Authority, British Nuclear Group and Nexia Solutions Ltd and several academic staff and students from the School of Materials at Manchester also attended. The objective of the meeting was to help to develop proposals for collaborative research between the University and the industry on key materials issues concerning

the processing, packaging and storage of nuclear wastes. In particular, the meeting focussed on the performance of the current waste containers and the scope for achieving a much longer lifetime in future designs.

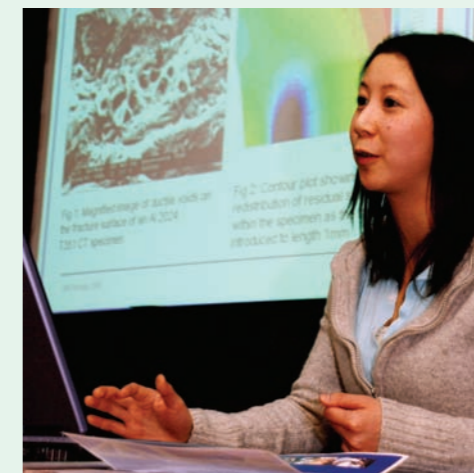
The meeting was punctuated by an MPC lunchtime seminar in which PhD student Jonathan Duff reported the latest results from his research into radiation-induced sensitisation in stainless steel and Dave Hodgson of Metalys Ltd explained the operation of the Frey process for the electro-winning of high-value refractory metals.

The meeting was one of a continuing series aimed at encouraging industry/academic collaboration. Further meetings on graphite and materials modelling are planned for the future.

OPEN DAY AT THE SCHOOL OF MATERIALS

The School of Materials held an Open Day last month at the Materials Science Centre and the MPC was strongly represented at this event. Open Days are an opportunity for prospective postgraduate students to discover more about teaching and research within the School and meet some of the academic staff and students. This event was an opportunity for Professor Andrew Sherry, Director of the MPC, to showcase the Centre and the research opportunities it is currently offering, which include several PhD studentships and an exciting summer internship programme. Prospective students also had a chance to meet and hear from two of the Centre's PhD students, Lai Mei Li (pictured), whose research concentrates on the plastic deformation of metals using electron diffraction and Fabio Scenini whose project aims to understand stress corrosion cracking. As well as presenting their research, Fabio and Lai Mei spoke about what it is like to be postgraduate student in the MPC, highlighting the close links the centre has with industry and the multi-disciplinary environment in which research is

carried out. Overflowing with enthusiasm, and impeccably delivered, their talks cannot have failed to impress the prospective students, some of which might soon be working alongside them. Dates for future open days are advertised on the School of Materials website.



UNIT FOR STRESS AND DAMAGE CHARACTERISATION



Professor Philip Withers, an Associate Director of the Materials Performance Centre, is the Director of the Unit for Stress and Damage Characterisation, a unit in the School of Materials, The University of Manchester. The Unit is a world leading research laboratory in stress and damage characterisation and this expertise is a good asset to the MPC. The Unit collaborates with over 30 University groups in the UK as well as over 40 industrial companies and is the only UKAS accredited Unit for x-ray stress measurement.

The expertise in the Unit covers four main areas:

- Measurement of stress and strain – this area includes Raman spectroscopy (portable optic fibre and microscope based), neutron diffraction (at central facilities), synchrotron diffraction (at central facilities), laboratory X-ray stress measurement, X-ray diffractometry, hole drilling and other destructive techniques, and magnetic characterisation of stress and microstructure.
- Measurement of surface displacements – this is performed using image correlation techniques and speckle pattern interferometry.
- Near surface performance – this includes a mechanical properties microprobe (nanoindenter), a Z-contrast acoustic microscope, and thermal diffusivity.
- Defect characterisation – this area includes X-ray tomography, Hertzian indentation methods, and a C-scanner.

In addition, the Unit's capability has recently been extended by the acquisition of a £1 million dual beam focussed ion beam microscope enabling micromachining to reveal crack tip and defect morphologies at the nanoscale.

For more information, please contact Professor Philip Withers (philip.withers@manchester.ac.uk or 0161 306 8872).

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Front Cover Image
High Level Waste Containers.
Courtesy of Nexia Solutions.