

*Queen's University – Rick Holt IRC  
– Mark Daymond*

Report on the NSERC-OPG-COG-Nu-Tech Industry Research Chair program in Nuclear Materials



Overview

The chair was renewed for its second term on February 1, 2007 with Prof. R.A. Holt as the chair and Prof. M.R. Daymond as associate chair. OPG and COG funding are now funneled through UNENE. In August 2009 a new faculty member Zhongwen Yao joined the group. Previously Zhongwen was a post-doctoral fellow at Oxford, studying radiation damage in materials for fusion reactors.

Research Program

The specific goals are to understand the anisotropic behaviour of pressure tube material, over a wide range of crystallographic textures and microstructures and to relate this to the elongation of pressure tubes, their increase in diameter, their sag and their fracture characteristics. The research currently concentrates on the effect of manufacturing variables on the properties, microstructure and texture of pressure tubes, the anisotropic creep of Zr-2.5Nb, the plastic anisotropy of Zr-2.5Nb, Zircaloy-2 and Excel alloy (Zr-3.5%Sn, 1%Nb, 1%Mo), the behaviour of hydrides in bulk Zr-2.5Nb, delayed hydride cracking of Zr-2.5Nb and the mechanical behaviour of Ni alloy steam generator tubing (with additional funding).

Research Facilities

In addition to the creep laboratory established at Queen's during the first term of the chair program, neutron scattering facilities and synchrotron radiation facilities in the UK (Rutherford Appleton Labs) and the USA (Los Alamos National Lab, Argonne National Lab, Brookhaven National Lab) as well as Canada (CRL) have proven very effective in pursuing the research goals, and profitable collaborations are continuing at these laboratories. In addition, facilities for strain measurement using both image correlation and laser speckle interferometry have been obtained via non-Chair research grants; these will be used for Chair research e.g. mapping of strain fields around crack tips. M. Daymond shared a combined CFI/ORF grant of \$790k with K. Pilkey of the Mechanical and Materials Engineering department to purchase a micro-X-ray computerized tomography system, recently installed in Nicol Hall. This system is capable of imaging large hydrides in Zr alloys.

In June 2009, the Canadian Foundation for Innovation announced a ~\$7M grant to Queen's as part of a \$17.5M project to build a Nuclear Materials Testing Laboratory, comprising a new building, a 4MV tandem accelerator, two new electron microscopes,

and other testing equipment. Provincial funding of ~\$7M was unofficially announced in August. The remaining funds are provided by Queen's (~\$1.6M) and in-kind contributions from equipment suppliers (~\$1.9M).

### Research Team

During 2007/09 the research team comprised senior research associates S.A. Aldridge and B. Szpunar, postdoctoral fellows A. Mark (now at University of Manchester), C. Mareau, A. Khan and C. Hamlin, Ph.D students W. Li (successful dissertation August 2009, now with College of the North Atlantic), F.Xu (successful dissertation November 2007, now with AECL SP), S. Cai (successful dissertation September 2008, now with Fort Wayne Metals), M. Kerr (successful dissertation September 2009, now with NRC Washington), and M. Sattari, H. Abdolvand and C. Nam (co-supervised with J. Szpunar at McGill, now with Nuclear Safety Solutions), M.Sc. students C. Judge (successful dissertation July 2009, now with AECL CRL) R. Sandaramoorthy (successful dissertation 2009 April, now a research assistant within the group), R. Toda, P. Mosbrucker, S. Goldthorpe, G. Allen, E. Tulk, and M. Swain, and undergraduate students C. Cochrane, D. Thorne, P. Molina, and J. Huneault. A new Ph.D student Y. Idrees and new M.Sc. students D. Campbell, L. Liao, T. Skippon and S. Wan joined the group in September 2009.

### Interaction with Industry, Universities and Other Organizations

Prof. Holt continues a strong interaction with the industry sponsors as an external consultant for AECL, Bruce Power and OPG (through Kinectrics Inc), as a reviewer and a member of the COG Fuel Channels Technical Committee and the COG Fuel Channel Deformation Working Group. Prof. Daymond is a member of the COG Fuel Channel Working Group on Crack Initiation and Fracture, as well as acting as an external consultant for AECL. Both Profs. Holt and Daymond collaborate with AECL, Kinectrics and Nu-Tech precision metals on a number of research topics.

In January 2009, 18 members of the Queen's Nuclear Materials group participated in the COG Fuel Channels Seminar in King City, Ontario. Students and post-doctoral fellows from the group made nine poster presentations describing their research.

In June 2009, Queen's organized a session within the Canadian Materials Science Conference on the subject of Nuclear Materials, as well as an instructional workshop on Nuclear Materials the day before the conference. Both workshop (40+ attendees) and session (2<sup>nd</sup> largest specific subject area in conference) were extremely well received with 14 graduate students and postdoctoral fellows from Queen's, RMC, UWO, McMaster and U. Alberta making oral presentations in the subject area.

The Chair-holders collaborated within Queen's University, and with McGill University (where Holt co-supervises a Ph.D student), the Royal Military College of Canada, the National Research Council of Canada (NRC), Pennsylvania State University, Los Alamos National Laboratories (USA), the Open University (where Daymond co-supervises a Ph.D student) and the University of Manchester (UK). Experiments were been carried out in collaboration with NRC scientists at Chalk River Laboratories, and at

Rutherford-Appleton Laboratories (UK), the Los Alamos National Laboratory, Argonne National Laboratory and Brookhaven National Laboratory(USA) with several student visits to these laboratories.

### Research Results

Research results were published in six theses, 24 refereed Journal papers, 13 presentations at international conferences, two COG reports and nine posters at the COG Fuel Channels Seminar, as follows.

### Theses

1. *Lattice Strain and Texture Evolution during Room Temperature Deformation in Zircaloy-2*, F. Xu, December 2007 (Ph.D.).
2. *Evolution of Interphase and Intergranular Strain in Zr-Nb Alloys during Deformation at Room Temperature*, S. Cai, September 2008 (Ph.D.).
3. *Initiation of Delayed Hydride Cracking in Zr-2.5Nb Micro-Pressure Tubes*, R.K. Sundaramoorthy, April 2009 (M.Sc.).
4. *Effect of Texture on Anisotropic Thermal Creep of Pressurized Zr-2.5Nb tubes*, W. Li, August 2009 (Ph.D.).
5. *Lattice Strain and Texture of Plastically Deformed Zircaloy-2 at 77K*, C.D. Judge, September 2009 (M.Sc.).
6. *Mechanical Characterization of Zirconium Hydrides with high energy X-ray Diffraction*, M. Kerr, September 2009 (Ph.D.).

### Refereed Journals

1. *Effect of Texture on Anisotropic Creep of Zr-2.5 Nb Tubes*, W. Li and R.A. Holt, Mater. Sci. Forum, Vols. 39-543 (2007) pp 3353-3358.
2. *Evolution of Inter-phase Stress in Zr-2.5%Nb During Deformation*, S. Cai, M.R. Daymond, R.A. Holt and E.C. Oliver, Advanced Materials Research, Vols. 15-17 (2007) pp 615-620.
3. *Evidence of variation in slip mode in a polycrystalline nickel-base superalloy with change in temperature from neutron diffraction strain measurements*, Daymond, M.R., Preuss, M., Clausen, B., Acta Mater. 55(9), p3089-3102 (2007).
4. *Evolution of Lattice Strains in Three Dimensions during In-situ Compression of Textured Zircaloy-2*, Xu, F., Holt, R.A., Oliver, E.C., Daymond, M.R., J. Neutron Research, v15, p121-130. (2007).
5. *Determination and Interpretation of texture evolution during deformation of a zirconium alloy*, Allen, V.M., Quinta da Fonseca, J., Preuss, M., Robson, J.D., Daymond, M.R., Comstock, R.J., J. ASTM Int., 5(1), JAI101255 (2007).
6. *Load partitioning between ferrite and cementite during elastic-plastic deformation of an ultrahigh-carbon steel*, Young, M.L., Almer J.D., Daymond, M.R., Haefner, D.R. and Dunand, D.C., Acta Mater., 55(6) p1999-2011, (2007)
7. *Strain and texture evolution during mechanical loading of a crack tip in martensitic shape-memory NiTi*, Daymond, M.R., Young, M.L., Almer J.D., and Dunand, D.C., Acta Mater., 55(11) 3929-3942, (2007)

8. *Investigation of Residual Stress in a Bent Ti-clad Cu Bus-bar by Neutron Diffraction and Finite Element Modeling*, F. Xu, J.C. Fredette, R.A. Holt, R.B. Rogge, D. Pickard and L. Tuck, *Journal of Neutron Research*, Vol 15, 2007, pp 259-266.
9. *In-reactor Deformation of Cold-Worked Zr-2.5Nb Pressure Tubes*, R.A. Holt, *J. Nucl. Mater.* 372 (2008) pp 182-214.
10. *Effect of Fast Neutron Fluence on the Anisotropy of In-reactor Creep of Zr-2.5Nb Tubes*, R.A. Holt, G.A. Bickel and N. Christodoulou, *J. Nucl. Mater.* 373 (2008) pp 130-136.
11. *Experimental study of Development of Internal Strains during Uni-axial Deformation in Textured Zircaloy-2*, F. Xu, R.A. Holt, M.R. Daymond, R.B. Rogge and E.C. Oliver, *Mater. Sci. and Eng. A*, Vol. 488 (2008) 172-185.
12. *Modeling the Development of Internal Strains during Uni-axial Deformation in Textured Zircaloy-2*, F. Xu, R.A. Holt and M.R. Daymond, *Acta Materialia*, Vol. 56 (2008) pp 3672-3687.
13. *Evidence for Basal  $\langle a \rangle$ -slip in Zircaloy-2 at Room Temperature from Polycrystalline Modeling*, F. Xu, R.A. Holt and M.R. Daymond, *J. Nucl. Mater.* 373 (2008), p217-225.
14. *A Finite Element Model of Deformation Twinning in Zirconium*, Y. Zhang, M.R. Daymond and R.A. Holt, *Mater. Sci. Eng. A* 473 (2008) 139-146.
15. *Inter-granular and Inter-phase Constraints in Zirconium Alloys*, R. A. Holt, M.R. Daymond, F. Xu and S. Cai, *J. ASTM International*, 5 (2008) paper JAI101304..
16. *In-Reactor Deformation of Zirconium Alloy Components*, R.A. Holt, *J. ASTM International*, 5 (2009) paper JAI101354.
17. *Determination and Interpretation of Texture Evolution during Deformation of a Zirconium Alloy*, V.M. Allen, J. Quinta da Fonseca, M. Preuss, J.D. Robson, M.R. Daymond and R.J. Comstock, *J. ASTM International*, 5 (2009) paper JAI101256.
18. *Strain Evolution in Zirconium Hydride Embedded in a Zircaloy-2 Matrix*, M. Kerr, M.R. Daymond, R.A. Holt, J.D. Almer, *J. Nucl. Mater.*, 380 (2008) pp70-75.
19. *Modeling Texture Evolution during Uni-axial Deformation of Zircaloy-2*, F. Xu, R.A. Holt and M.R. Daymond, *J. Nucl. Mater.*, 394 (2009) pp 9-19.
20. *Modeling the Room Temperature Deformation a Two Phase Zirconium Alloy*, S. Cai, M.R. Daymond and R.A. Holt, *Acta Mater.*, Vol. 57 (2009) pp 407-419
21. *Evolution of Interphase and Intergranular Stresses in Zr-2.5Nb during Deformation*, S. Cai, M.R. Daymond, R.A. Holt, M.A. Gharghoury and E.C. Oliver, *Mater. Sci. Eng.*, 501 (2009) pp 166-181.
22. *Elastic and Plastic properties of  $\square_{Zr}$  at Room Temperature*, S. Cai, M.R. Daymond, R.A. Holt and E.C. Oliver, *Journal of Nuclear Materials*, 393 (2009) pp 67-76.
23. *Study of residual elastic- and plastic-deformation in uniaxial tensile strained nickel-based Alloy 600 samples by polychromatic X-ray microdiffraction (PXM) and neutron diffraction methods*, Jing Chao, Alison Mark, Marina L. Suominen Fuller, N. Stewart McIntyre, Richard A. Holt, Robert J. Klassen, Wenjing Liu, *Materials Science and Engineering A*, 524 (2009) pp20-27
24. *Fracture of a minority phase at a stress concentration observed with synchrotron x-ray diffraction*, M. Kerr, M.R. Daymond, R.A. Holt, J.D. Almer, S Stafford and K.B. Colas, *Scripta Materialia* 61 (2009) pp 939-942.

#### International Conference Presentations

1. *Orientation of Hydrides in Zr-2.5Nb Tubes under Biaxial Stress*, J.C. Fredette, V. Perovic and R.A. Holt, 14<sup>th</sup> ASTM International Symposium on Zirconium in the Nuclear Industry, Sunriver Oregon, June 2007.

2. *In-Reactor Deformation of Zirconium Alloy Components*, R.A. Holt, 14<sup>th</sup> ASTM International Symposium on Zirconium in the Nuclear Industry, Sunriver Oregon, June 2007 (invited).
3. *Inter-granular and Inter-phase Constraints in Zirconium Alloys*, R.A. Holt, M.R. Daymond, F. Xu, S. Cai, 14<sup>th</sup> ASTM International Symposium on Zirconium in the Nuclear Industry, Sunriver Oregon, June 2007.
4. *Insights into the deformation mechanisms of hexagonal metals*, M.R. Daymond, Invited talk at the Denver X-ray Conference, Denver Colorado, July 2007.
5. *Influence of internal stresses on texture inheritance through the alpha-beta phase transformation in zirconium*, M.R. Daymond, P. Mosbrucker, S. Cai, R.A. Holt, Meca-Sens IV, Vienna Austria, September 2007.
6. *Inter-granular and Inter-phase Constraints in Zirconium Alloys*, R. A. Holt and M.R. Daymond, 2008 Conference of the American Society for Neutron Scattering, Santa Fe, April 2008.
7. *Texture Inheritance and Variant Selection through the Alpha-Beta Phase Transformation in Zr2.5Nb*, M.R. Daymond, R.A. Holt, S. Cai and S. Vogel, International Conference on Texture of Materials, Pittsburgh, June 2008
8. *Stress changes in parent and child grains due to twinning*, M.R. Daymond, R.A. Holt, R. Zhang, F. Xu, International Conference on Residual Stress, Denver, August 2008 (session opening, invited).
9. *Modeling and Measurement of Residual Macro and Lattice Strains during Four-point Bending of Zircaloy-2*, F. Xu, R.A. Holt, M.R. Daymond, R.B. Rogge, International Conference on Residual Stress, Denver, August 2008.
10. *Neutron diffraction study of intergranular stress development in Zr-2.5%Nb pressure tubes*, O. Zanellato, M.E. Fitzpatrick, M.R. Daymond, L. Edwards, International Conference on Residual Stress, Denver, August 2008.
11. *Impact of Zirconium Hydride Precipitates on Fracture of a Zirconium Alloy*, M. Kerr, M.R. Daymond, R.A. Holt, J.D. Almer, International Conference on Residual Stress, Denver, August 2008.
12. *Impact of Zirconium Hydrides on Fracture of Zirconium alloys*, M. Kerr, M.R. Daymond, R.A. Holt, J.D. Almer, 12<sup>th</sup> International Conference on Fracture and Fatigue, Ottawa, July 2009.
13. *Strain Measurements of Crack tip Hydrides*, M. Kerr, M.R. Daymond, R.A. Holt, S. Stafford, J.D. Almer, Denver X-ray Conference, August 2009 (session opening, invited)

### Reports

1. *In-service Deformation of Pressure Tubes*, R.A. Holt, CANDU Owners Group Report OP 07-132 (March 2007)
2. *SOTAR (State of the Art Report) on Contact Prediction*, S. Khajepou, E. Nadeau and R.A. Holt, COG Report COG-07-1046, (November 2007)

### Posters at COG Fuel Channels Seminar (January 2009)

1. *Micromechanical Modeling of Twinning in Zirconium*, C. Mareau
2. *Thermal Creep of Pressurized Zr-2.5Nb Tubes with Different Textures*, W. Li
3. *Modeling of Anisotropic Creep of Pressurized Zr-2.5Nb Tubes*, W. Li and F. Xu
4. *Plane Strain Tensile Deformation of Inconel 690*, R. Toda
5. *Texture Evolution and Variant Selection in Zr-2.5Nb during the  $\alpha$ - $\beta$  Phase*

*Transformation*, P. Mosbrucker

6. *Microstructure of Excel Alloy Pressure Tubes for Generation-4 Reactors*, M. Sattari
7. *Initiation of DHC in Zr-2.5Nb Micro-pressure Tubes*, R. K. Sandaramoorthy
8. *Proposed Experimental Analysis of Hydrides in Zr-2.5Nb Micro Pressure Tubes*, S. Goldthorpe
9. *Strain Mapping of Crack Tip Hydrides with High Energy X-Ray Diffraction and Scanning Electron Microscopy*, M. Kerr and S. Stafford (Kinectircs Inc.)

### Teaching

The senior/graduate level course in Nuclear Materials course was taught in winter 2009 by Profs. Holt and Daymond to the UNENE M.Eng program at Durham College, and by Holt to fourth year undergraduates and graduate students at Queen's in the fall semester of 2007 and the winter semester of 2008. A shortened version of the course was given three times to a total of ~60 employees of AECL, OPG and Kinectrics in 2007 May/June, 2008 Jan/Feb and 2008 May/June.

### Other

At the 14<sup>th</sup> International Symposium on Zirconium in the Nuclear Industry in June 2007, Prof. Holt was awarded the 24<sup>th</sup> W.J. Kroll Medal by the American Society for Testing and Materials for "unique and lasting contributions to the technology of zirconium". The medal recognized his work identifying and describing in-reactor deformation mechanisms of materials and structures used in nuclear reactors.

Prof. Daymond was promoted to the rank of Professor, active 1<sup>st</sup> July 2008.