CONTENTS

BIOMECHANICS
Image-guided Percutaneous Scaphoid Fixation using Intraoperative 3D Fluoroscopy
Erin J. Smith

Image-guided Robotic Gynaecological Brachytherapy (RoboGyn)
Yashar Madjidi

ENERGY-FLUIDS
The Effect of Waveform Shape and Mean on the Flow in Endovascular Stents
Amirreza Rouhi, Matthew Ford and Ugo Piomelli

Thermal Optimization of an Electric Vehicle Battery Cooling Plate with multiple curved channels
Ben Banks

Modelling and Experimental Evaluation of a Liquid Desiccant Air-conditioning System with Solar Thermal Regeneration
Lisa Crofoot

Development of Coupled Physics Codes to Solve for Electrochemical Reaction and Transport in Numerically Reconstructed Electrodes
Duncan Gaweł

Passive control of turbulence in a round free jet
H. Sadeghi and A. Pollard

Evaluation of CFD Prediction of Drag Force over a Cowled Ejector
Katherine Little

Dense Particle Cloud Dispersion by a Shock Wave
Mark Kellenberger

Detonation cell Size Data for Dimethyl-ether Air Mixtures
Peter Diakow

Thermoelectric Heat Pump: Characterization of Performance in Heating Mode
Nate Preston

Large eddy simulation of boundary layer/wall jet with embedded spanwise vortices
Wen Wu
MANUFACTURING and DESIGN

Student Perspectives on Engineering Design Education – A Work in Progress
Richard Aleong

Fuzzy Adaptive PID Position Control of a Pneumatic Gantry Robot
Behrad Dehghan

Fixed Beam Laser Welding of Alumina Ceramic Plates
Blake Sedore

Electrically Assisted Single Point Incremental Forming
David Adams

Optimization Tool Development for Pack-Level Electric Vehicle Battery Cooling
Jeremy Bakker

Reducing the Effects of MRI Acoustic Noise using Micro-Perforated Panels
Rob Fraser

Failure Analysis of Parallel Manipulators
Vahid Nazari

MTO Project: Improving Haul Truck Fuel Efficiency
Vladimir Vukovic

MATERIALS

Dependence of the Local Texture, Defect Structure, and Chemistry on the Annealing Response of an AA6XXX/AA3003 Clad System
Alex Penlington

Development of High Dielectric Constant Ceramic Films Using Multilayer Electrophoretic Deposition of BaTiO₃
Berkan Harari

Study of the Effect of Strain Rate on Deformation Mechanisms of a Two-Phase Zirconium Alloy Using Synchotron X-Ray Diffraction
Chris Cochrane

Predicting Corrosion Initiation Sites in Copper Using Finite Element Modeling
Connor Kemp

Temperature dependence of the uniaxial deformation behavior of Zircaloy-2 alloy
Fei Long

The Effect of Microstructure on the Mechanical Behaviour of Dual-Phase Steels
Hossein Seyedrezai
Effects of microstructure on tensile behaviour in aluminum-containing TRIP steel
Jasmine Chiang

Study on Thermal Creep of Zr-Excel Alloy by Modification of Crystallographic Texture
Kazi Ahmmed

In-situ TEM Study of Irradiation Induced Damage in CANDU Garter Spring Material Inconel® X-750
Ken He Zhang

Investigating the Effect of Cooling Rate on the Microstructure and DHC Behavior of Zr-2.5Nb Alloy
Louis Liao

An investigation of twinning in three dimensions
Marta Majkut

Texture Analysis of Metallographic Image with Applications in DHC study
Qiang Fang

Molecular Dynamics Simulation of Displacement Cascades in α-Zr
Sali Di

Measurement of Stress Relaxation at Notch Tips in Zr-2.5Nb Using Synchrotron X-Ray Diffraction
Shuai Wan

Use of a Genetic Algorithm for Optimization of a Plasticity Code
Travis Skippon

In-Situ Study of Heavy Ion Irradiation In Pure Zirconium
Yasir Idrees
Introduction and Background

The scaphoid is one of the eight small carpal bones comprising the human wrist, situated just at the base of the thumb. It is the most commonly fractured carpal bone, typically resulting from a fall on an outstretched hand. Casting is the standard treatment for uncomplicated fractures, but limits mobility, and therefore percutaneous internal fixation is gaining popularity as a treatment alternative. The procedure involves drilling a guidewire along the length of the scaphoid over which a cannulated screw is placed. Both the wire and screw are inserted through the skin, requiring liberal x-ray imaging and posing an occupational hazard to surgeons who routinely perform these procedures. The mechanical stability and clinical outcome of the procedure have been linked to central screw placement and minimizing cortical breach, both of which can be difficult to achieve with conventional techniques.

Computer-assisted surgery has demonstrated improvements in accuracy and reduction in x-ray exposure in other orthopedic pin insertion procedures; however, the typical computer-assisted workflow does not translate easily to this procedure. A standard tracking device cannot be attached directly to the scaphoid for navigation due to the small size of this bone. Because the procedure is performed with minimal invasion (percutaneously), registering the images for navigation by collecting surface points on the scaphoid (i.e., patient-based registration), is counter-productive.

Recent developments in flat-panel fluoroscopy have made 3D cone-beam computed-tomography (CT) feasible for intraoperative use, and an ideal instrument to conduct image-guided navigation. This work aimed to use this technology to develop and test an image-guided navigation system for percutaneous scaphoid pinning and compare this to conventional approaches.

Methods

Two image-guided approaches were developed and tested: the first using volume-rendering of the 3D images similar to digitally-reconstructed radiographs, and the second using volume-slicing comparable to CT slices. Both methods made use of a 3D digital fluoroscopic “Innova” C-arm (GE Healthcare, France) that could rotate 360° about an isocentre to take a 3D cone-beam CT image. Navigation was performed using a ceiling-mounted optical tracking camera and active infrared markers attached to the wrist and drill guide. A preoperative calibration was performed to establish a spatial relationship between the internal coordinates of the imager and the tracking system; this allowed an intraoperative image to be used for navigation, without the need for patient-based registration or imager tracking.

Each navigated procedure began by taking a 3D image of the wrist and rendering it according to one of the two image-guidance methods. A surgeon used these images to create a preoperative plan by positioning a virtual drill path on the scaphoid. To navigate the plan, the real-time position of the drill was displayed relative to the wrist image on a computer monitor, by applying the preoperative calibration relationship to the pose data of the tracked drill guide (Figure 1).

![Figure 1: Image-guided trial. (a) The real-time position of the drill is shown on to the surgeon on a computer monitor to navigate the procedure. (b) Screen capture of an image-guided procedure showing the drill (purple/green stylus) relative to a volume-rendered image (left) and volume-sliced image (right).](image)

Randomized trials were conducted in which both navigated techniques were compared to two conventional methods. The first conventional method utilized a standard fluoroscopic C-arm with 2D x-ray images, while the second used the Innovia digital C-arm, but in 2D mode, analogous to a standard C-arm, except with digital imaging and magnification. Each study group had 24 trials.

The morphology of the scaphoid is highly variable, thus a model wrist with a replaceable scaphoid was selected as the basis for this study in order to permit direct comparison between the trial groups. The surgical goal was to insert a guidewire along the central axis of a model scaphoid to maximize both length and depth. After each trial, the scaphoid was removed with the wire intact and imaged using CT to generate 3D surface models of the drilled scaphoid. Algorithms were developed to determine the length of the drill path and the shortest distance from the drill path to the scaphoid surface, to be used as comparative measures of centricity. A virtual screw was positioned along the drill path to assess if cortical breach would have occurred.

Procedure time, drilling attempts and radiation exposure were also recorded for each trial.

Results

Both image-guided approaches improved the precision of central guidewire placement compared to the conventional techniques (p<0.01). Volume-slicing resulted in increased length of the drill path (p<0.1). Volume-rendering reduced the incidence of simulated cortical breach. Fewer drilling attempts were required using both image-guided approaches (p<0.01), but both navigated approaches took longer to perform than conventional techniques (p<0.05). Image-guidance also significantly reduced x-ray exposure (p<0.01).

Discussion and Conclusion

Image-guidance achieved a more repeatable and reliable central pin placement, with fewer drill passes and with less radiation than conventional 2D techniques. Although both image-guided procedure times were significantly longer than the conventional techniques, likely due to the additional planning step, the average time for both image-guided procedures was under 4 minutes, well within the clinically-acceptable time frame. The positive performance in this preliminary study supports the progress of this technology for facilitating percutaneous scaphoid fixation.

This in-vitro study was a constrained evaluation to test our workflow for image-guided scaphoid fixation. This novel navigation technique does not require preoperative imaging or patient-based registration that is typical of most computer-assisted workflows. Another potential benefit may also include reduced radiation exposure to the surgical team. The next step will be to evaluate this technology under more realistic conditions using an ex-vivo model. Presently, a wrist positioning device is being evaluated for a cadaver study to secure the scaphoid and allow the wrist to be tracked for navigation.
Background and Rationale

Gynaecological cancer is the second most common cancer among women worldwide. Cervical cancer with more than 500 000 new cases annually, as one of six gynaecological cancers, has high mortality rate of 1 person in less than every 2 minutes throughout the world. Brachytherapy is found to be the most effective minimally invasive cancer treatment option especially for cervical cases when radiation sources are placed closed to the tumorous regions. Less constraining needle templates, optimized needle insertion techniques for more planable insertion trajectory through curved needle guides, immobilization of the targeted organ during needle insertion, and more realistic physic-based needle insertion modeling are some of the main mechanical-oriented refinements that can be potentially improve gynaecological brachytherapy. This project was launched in 2010 as a collaborative effort between the Austrian Center for Medical Innovation and Technology (ACMIT), Medical University of Vienna and Queen's University. The mechanical engineering aspects of RoboGyn comprise the subject matter of the author's PhD dissertation research.

Introduction

Over the last two decades, substantial improvements have been made in biorobotics. To achieve practically reliable precise needle targeting in gynaecological brachytherapy, improvements can be pointed out as: • Using advanced imaging modalities for navigation and realistic 3D volumetric model of targeted region. • Refinements in needle manufacturing technology and triggering mechanisms. • Realistic physic-based tool-tissue interaction modeling of needle-based procedures including tissue deformation and organ motion. • Ultimately incorporating robotic assistant system for needle guidance and placement procedures. The current study has been presented in order to improve the gynaecological brachytherapy procedure while focusing mainly on the last three aforementioned improvement aspects in two main subtopics: (1) design, prototyping, and implementation of miniature manipulator (needle guide) for image-guided gynaecologic brachytherapy interventions, (2) investigation of different hybrid oscillational needle insertion techniques to increase needle targeting accuracy in multilayer soft tissue structure with the use in intracavitary needle guide.

Methods and Results

The experimental setup comprises three main stages: (1) insertion platform: a preloaded non-back drivable fast double pitch lead screw coupled with reliable DC motor package has been chosen to provide high precision zero-backlash linear motion with maximum carriage (travel) speed of 50mm/s and stroke length of 200mm. A 4DOF phantom box was designed and prototyped to enable BC-dependant motion study of the modeled uterus in contact with neighboring organs and supporting structures in female pelvic floor. This platform equipped with a sensorized needle gripper to monitor the force/torque and trajectory of needle (Fig.1). (2) needle drive: a novel hybrid oscillational needle drive was designed and prototyped with possibility of separate adjustable amplitudes and frequencies for translational and rotational oscillation. It provides the desired needle motions to perform series of insertion experiments on the implemented insertion platform. (3) needle guide (applicator): a new passive needle guide (gynaecological applicator) was designed and prototyped to perform the insertion experiments after selection of the optimized needle motions. General work space of operational access for the targeted area has been modeled to design the active needle guide (miniature manipulator) for next stage (Fig.2).

For straight needle insertion, during the separate translational and rotational oscillation, the maximum translational frequency with small amplitude (TF4TA1) and the maximum rotational frequency with big amplitude were selected for the final comparison with the selected hybrid oscillational needle insertion. Also the hybrid oscillational pattern with the least insertion velocity dependent behavior was selected to compare with other patterns. As shown in Fig.3, at high clinically feasible insertion speed, the needle force as low as 0.5N was acquired from F/T sensor while performing the selected hybrid oscillation which is incomparable with even pure translational oscillation pattern. Moreover, because of enjoying fast rotational oscillation, the organ motion is also expected much lower than pure translational pattern.

Continuing Work

The next stages this project will be conducted in developing the required experimental setup and experimental validation for the integrated prototype of the whole system. The experimental set up will be developed with the clinically testable modified version of proposed passive applicator and the laboratorial version of the newly designed miniature manipulator (active applicator). The next insertion experiments will be performed through the proposed curved needle guides (active/passive). Comparative procedure assessments will be also conducted with the ability of boundary condition-dependant organ motion study.
The Effect of Waveform Shape and Mean on the Flow in Endovascular Stents

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Synopsis
Atherosclerosis is a cardiovascular disease which occurs by the built up of fatty tissues on the internal artery wall. It was found that there is a strong correlation between the locations where the biological molecules are accumulated (that leads to atherosclerosis) and some fluid mechanical parameters (Wentzel et al [1]). The flow in arteries has a wavy periodic behavior due to the pumping processes by heart valves. In this study the effect of the waveform shape and mean is studied on the related fluid mechanical parameters. Since the imposed waveform is negative during the cycle a vortex will be created and migrate toward the center of the channel[2]. The effect of waveform shape and mean is studied. It was found that the distribution of near wall parameters and timing of vortices can be linked to the the exact solution of the unsteady channel flow. Finally in order to study the effect of the presence of the stent on the distribution of biological particles, a Lagrangian particle tracking routine based on the model originated from Maxey & Riley [3] was developed and validated.

Introduction
Atherosclerosis is one type of Cardiovascular disease which occurs by the built up of fatty tissues on the internal artery wall. Charonko et al. [2] used PIV to study the kinematics of the flow with a waveform with reversed flow and observed a large vortex created between two stent struts which migrates toward the center of the channel. Here the problem was studied from numerical and mathematical point of view and a parametric study was performed to see the variation of the shape of the waveform and Reynolds number on both kinematics and dynamics of the flow.

Methods and Results
The fluid part of the problem was simulated using a well-validated staggered finite-difference code. The original waveform used by Charonko was reconstructed by Fourier decomposition and different number of modes were used to study the shape of the waveform. A particle tracking routine based on the original equation by Maxey & Riley [3] was developed and validated to study the effect of the stents on the distribution of platelets.

Conclusion
Studying both dynamics and kinematics of the flow revealed that the presence of the stent does not cause significant disturbance on the flow especially when the stent has large inter-strut spacing and has unidirectional shape. Therefore by this way both dynamics and kinematics of the flow can be linked to the exact solution of unsteady Poiseuille flow. By this way a modal analysis was made for the effect of the mean Reynolds number (mean flow) on the timing of vortex lift-off to study the importance of the modes on the kinematics of the flow.

References
Thermal Optimization of an Electric Vehicle Battery Cooling Plate with multiple curved channels

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Introduction

Electric vehicles (EVs) and hybrid electric vehicles (HEVs) rely heavily on batteries for power storage, be it from the drive train or sources such as regenerative breaking. Precise thermal management is needed to keep these batteries at optimal operating conditions. The performance and lifetime of batteries used in today’s EVs and HEVs are sensitive not only to the temperature they are running at, but to the small deviations in temperature across the cells.

Many previous studies have looked at single inlet and single outlet channels, and examined a variety of design geometries consisting of series, and parallel channels as well as single serpentine passages. The results of these studies were limited, however, in terms of using single inlets and outlets, and defining optimization in terms of choosing a result from a list of predetermined initial designs without further refinement of the geometry. These results also suggest that single channel systems perform much better then multi-channel systems however they look at it from the aspect of series and parallel channels originating from a single inlet and converging to a single outlet and do not consider the idea of multiple inlets and outlets to the cooling plate. [1,2,3,4]

The objective of this study was to perform shape optimization of a cooling cell consisting of multiple curved channels in a parallel configuration. The plate’s thermal behavior in terms of mean temperature and temperature uniformity was examined, along with its power consumption. These properties were examined using optimization algorithms and computational fluid dynamics (CFD) and optimal coolant channel geometries were determined for a number of performance characteristics. This paper examines the methods and results obtained and discusses the benefits of the study’s findings.

Methods and Results

The model used for CFD analysis was constructed using the pre-processor Gambit. It was designed around a 1mm thick plate with a width of 200mm and a height of 160mm. The model was simplified using symmetry through the thickness to create models that were 160mm×200mm×0.5mm which can be seen in Figure 1. The type and shape of the channels were based on previous work conducted [5] as well as design space exploration. Fluent was used as the CFD solver for the computations. The mesh was opened in Fluent and boundary conditions were applied to set the mass flow rate, heat flux and define the symmetry plane, mass flow inlet and the pressure outlet.

Optimization is run and managed through the Matlab program. The optimization uses a set of geometry parameters as design variables, which are constrained with conditions to ensure geometric integrity of the model and to limit situations which may cause a loss of convergence in the CFD solver. The objective functions for the optimization are the average temperature across the plate $T_{avg}$, the standard deviation of the temperature across the plate $T_{avg}$, and the pressure drop across the plate $P_{fluid}$. The optimization starts at an initial design and then optimizes the geometry for one of these objective functions until the convergence criteria has been met.

Figure 1: Example of design geometry (not to scale)

Figure 2: Design geometries for initial and optimized cooling plates.

Figure 3: Flowmap of optimized cooling plate.

Table 1: Numerical results of cooling plate optimizations

<table>
<thead>
<tr>
<th>Optimization</th>
<th>Objective function value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{max}$ (Pa)</td>
<td>$T_{avg}$ ($^\circ$C)</td>
</tr>
<tr>
<td>Initial</td>
<td>4597.3</td>
</tr>
<tr>
<td>$P_{max}$</td>
<td>864.0</td>
</tr>
<tr>
<td>$T_{avg}$</td>
<td>916.8</td>
</tr>
<tr>
<td>$T_{max}$</td>
<td>1429.6</td>
</tr>
</tbody>
</table>

From these results we can see that average temperature and pressure optimizations share many geometric similarities. They both tend towards larger open channels, with the pressure optimization tending towards flatter channels, and the average temperature optimization tending towards more surface area covered. This makes sense as the pressure loss will be lower in a wider flatter channel, while the average temperature will be reduced as more fluid passes over more surface area. The standard deviation optimization had very different design however. There is a notable increase in the amplitude of the later bends which suggests the optimization is attempting to balance the velocity of the fluid with the temperature change as it passes through the plate.

Table 2: Performance increase of cooling plate optimizations over initial design

<table>
<thead>
<tr>
<th>Optimization</th>
<th>Objective function value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{max}$ (Pa)</td>
<td>$T_{avg}$ ($^\circ$C)</td>
</tr>
<tr>
<td>Initial</td>
<td>81.21%</td>
</tr>
<tr>
<td>$P_{max}$</td>
<td>80.06%</td>
</tr>
<tr>
<td>$T_{max}$</td>
<td>68.90%</td>
</tr>
</tbody>
</table>

Conclusions

Optimization of a cooling plate has been performed using CFD and optimization algorithms, using a geometry defined by a number of design variables, and optimized for three separate objective functions. The optimizations showed dramatic improvements in the objective functions compared to initial designs, however the design space and certain design variables have been limited to ensure model integrity and convergence of the CFD. Future work will deal with relaxing model constraints, and deal with modified versions of the same channel shape to expand the scope of the design domain.

References

Modelling and Experimental Evaluation of a Liquid Desiccant Air-conditioning System with Solar Thermal Regeneration

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Synopsis
As part of an ongoing project that aims to demonstrate the benefits of solar cooling in Canada, a 95m² vacuum tube solar array was installed and instrumented to drive a pre-commercial Liquid Desiccant Air Conditioner (LDAC). In phase one of the study, the LDAC was tested using a gas-fired boiler and the performance was characterized. The second phase, now in progress, involves connecting the previously studied LDAC to an evacuated tube solar array. The array was designed and installed during the summer of 2011 and operating data is currently being collected.

Introduction
Air conditioning systems consume a significant amount of energy and contribute to peak electrical loads. Thermally driven systems using solar energy are an attractive alternative to traditional systems since the peak solar energy closely coincides with the air conditioning load. Liquid desiccant systems utilize the hygroscopic properties of a salt solution to dehumidify air. Ventilation air is brought into contact with concentrated desiccant solution in the conditioner, where water vapour is absorbed. This process releases the latent heat of condensation, which must be removed to maintain conditioner effectiveness. The diluted desiccant is then regenerated using low-grade heat. The novel low-flow LDAC system used for this demonstration consists of two parallel plate heat and mass exchangers, which are internally cooled and heated. Desiccant flows in a thin wick over the outside of the plates, while air is blown horizontally between the plates to allow for absorption and desorption of water vapour. The low desiccant flow rates eliminate carryover of desiccan which provides high-density (~1000MJ/m²) loss-less energy storage [1].

Methods and Results
Phase I testing of the system used a 90kW gas fired boiler as a heat source for the regenerator. Regeneration temperatures were varied from 50-90°C, similar to temperatures produced by flat plate and evacuated tube solar collectors. The performance was characterized using experimental results and modeled in TRNSYS. Higher regeneration temperatures were found to increase the system capacity and coefficient of performance. As a result, the solar array was designed using evacuated tubes solar collectors [2]. The system was designed and installed to have variable configurations. Figure 1 shows a simplified schematic of the solar driven desiccant system. The ground mount solar array (shown in Fig. 2) consists of 24 evacuated tube solar collectors, which provide 61m² of absorber area and cover a gross area of 95m². The collector circulator pump (P1) and pump between storage and regenerator (P2) are high efficiency, variable speed pumps that provide additional testing and control configurations. The gas-fired boiler provides auxiliary power for the LDAC and can be configured in series or parallel. The 65kW cooling tower is used to provide cooling water to the conditioner.

TRNSYS was used to model the solar LDAC system and simulations were used as a design tool to help size the array and storage tank components. It was predicted that the solar array would provide 65% of the required thermal input with solar collector efficiency (based on absorber area) of 65%. The LDAC unit was predicted to have an average thermal COP of 0.52 and latent cooling power between 13-23kW. The array is currently being operated with the dry cooler rejecting collected heat. Figure 3 shows the experimental operating data for September 18th 2011.

Future Work
Simulations of solar LDAC for different operating conditions will be validated with experimental data. The system will be improved and expanded by replacing inefficient pumps and fans and incorporating desiccant storage. Storage integration is expected to increase both solar fraction and solar utilization. The array will be monitored during the winter of 2011 to determine its capacity for space heating and evaluate the potential of a solar combi-system which provides space heating, cooling, and domestic hot water.

References
Development of Coupled Physics Codes to Solve for Electrochemical Reaction and Transport in Numerically Reconstructed Electrodes

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Synopsis
As part of a nationwide research network focused on improving Canadian solid oxide fuel cell (SOFC) technologies, a numerical model is being developed to evaluate the coupled transport phenomena within the electrode. The proposed model utilizes a numerical code to generate three-dimensional (3D) multiphase electrode geometries and a CFD software, OpenFOAM, to solve for the coupled species transport with in the electrode. To account for the electrochemical kinetics an equation is implemented at the interface between the three transport regions to dictate species production and consumption. The model will be used to compare the performances of numerical and experimental electrodes and to analyze structural properties important to SOFC performance.

Introduction
Fuel cells are energy conversion devices which convert chemical potential energy directly to electrical energy through electrochemical reactions which occur in the electrodes near the electrode-electrolyte interface. Solid oxide fuel cells are a type of fuel cell which operate at high temperatures (600°C to 1000°C), use a solid ceramic electrolyte and can run on hydrocarbon fuels. SOFC electrodes consist of a complex three phase structure which allows for the transport of electrons, ions and gases throughout the electrode. At the linear interfaces between the three phase boundaries the transport equations are coupled by an electrochemical reaction commonly expressed as the Butler–Volmer equation [3]. This equation is a function of the local electrical potential, ionic potential and the gas concentrations at the TPB [4]. In this study the anode electrode is being investigated and an example of a simplified anode structure and electrochemical reaction is shown in Figure 1[3].

Methods and Results
The electrode microstructures are generated using a numerical reconstruction code which uses a drop-and-roll algorithm to place spheres within the domain [1]. Utilization of this code allows for the easy manipulation of electrode properties and efficient production of multiple structures. The geometries are then imported into OpenFOAM where they are meshed using a body-fitting/cut-cell mesh algorithm. To allow for the transport regions to be coupled additional algorithms were written which correctly identify the TPB reaction sites and couple the multiphase regions. Figure 2 shows one phase of the generated geometry and the identified TPB lines. Due to the unique nature of the coupling transport equations, a new solver is being written in OpenFOAM to resolve the local Butler-Volmer equation and distribute the results throughout the geometry. Within the three regions electron and ion conduction is modelled using Ohm’s law and bulk gas diffusion is modelled using Fick’s law. Figure 3 illustrates a coupled potential field in the electron phase. In the current model arbitrary boundary conditions are implemented to apply potential and concentration fields throughout the three geometries. For simplicity the Butler–Volmer equation is replaced with a simplified coupling equation and Figure 4 shows an example of localized species production in a section of the electrode.

Future Work
In the future physical boundary conditions and Butler–Volmer equation will be implemented to allow for the performance of the anode to be determined. Knudsen diffusion within porous regime will also be added to increase the accuracy of the diffusion model. Obtaining performance results from geometries with varying parameters will also be looked at to begin to identify favorable structural properties. Collaborative model validation between numerical and experimental groups would also be carried out.

References
Passive control of turbulence in a round free jet

H. Sadeghi and A. Pollard

Introduction

There are three different regions that can be defined in the round jet: the near-field, the intermediate-field and the far-field. The near-field region is where the flow characteristics match those of the nozzle-exit, and is usually found within 0 ≤ x/D ≤ 6. The far-field region, located at approximately x/D > 30, is the fully-developed or self-similar region. The intermediate-field region lies between the near- and far-fields of the jet. The near- and intermediate-fields together comprise the development portion of the jet, where it often dominates practical applications of jets for which upstream conditions can significantly influence heat, mass, and momentum transfer. Therefore, the ability to control the flow development in this region would have a vital impact on many of those engineering applications. In the shear layer of the jet, vortex cores will form, evolve and pair-up to form large eddies because of the large velocity gradient in the radial direction. These large eddies break down and form smaller and smaller eddies, and the turbulence structures decrease in scale. Throughout this process, energy is transferred from the large-scale structures to the smaller scales in the outer layer. The control of turbulence in jet flows has been received much attention. Both active and passive methods have been applied to modify the statistical properties of turbulent jets. The aim of this work is to examine the effect of introducing a new length scale into the round, free turbulent jet using a fine ring.

Experimental Details

Air exits a settling chamber via a round duct to the inlet of smoothly contracting axisymmetric nozzle with exit diameter of Dₜₑₓ = 73.6 mm. The mean and rms velocity profile at the jet exit were carefully measured (x/Dₜₑₓ = 0.03) with a stationary single hot wire. A wire ring, with square cross-section, of sides h = 1.5 mm, and outer diameter Dₘᵦₓ = 71.6 mm was placed in the middle of the jet shear layer, at a stand-off distance downstream of the jet nozzle exit plane x/ Dₜₑₓ = 0.03. The ring was designed to enable computational studies to be considered using simple cylindrical-polar co-ordinates. Data were acquired using a flying and static hot-wire, at Re=30,000 (Re=Uₑₓ/ν). The flying hot wire was of order 2 m/sec and had a ramp up and ramp down distance of approximately 3Dₑₓ with flying hot wire data acquired over approximately 19Dₑₓ. Approximately 1100 “sweeps” through the domain (at r/R = 0) were acquired, which gave statistically converged ensemble averages of data throughout the interrogation volume. Static hot wire data were obtained in the region 0 ≤ x/Dₑₓ ≤ 6. The exit mean velocity profile is uniform over the range of 0 ≤ r/ Dₑₓ ≤ 0.45 and decreases to zero between 0.45 < r/ Dₑₓ ≤ 0.5 (inside the shear layer). It should be noted that the ring covers the distance of 0.466 ≤ r/ Dₑₓ ≤ 0.486.

Presentation and Discussion of Results

Figure 2 provides the evolution of centreline turbulence intensities (u/Uₑₓ). The data indicate good congruence between data obtained using both stationary (SHW) and flying hot wire (FHW). It is observed that the turbulence intensities are suppressed within the jet when the ring is used. Figures 3 and 4 display the power spectral density between 0.8 < x/Dₑₓ < 5 for both the unmodified and modified jets, respectively. All the samples were taken at a fixed location in the shear layer (r/Dₑₓ =0.476). For the unmodified jet and at x/Dₑₓ =0.8, the largest peak frequency is found at approximately fₛ =198 Hz. This is equivalent to a Strouhal number, Stₛₑₓ, of 0.017, which is within the expected range for the shear layer instability (Stₛₑₓ=0.03-0.04). The ring causes the roll-up of the initial shear layer (the shear layer mode). At streamwise locations farther downstream, the largest peaks shift to fₛ/2 and fₛ/4, which implies interactions of the shear layer instability structures. The spectra for the with-ring case (modified flow) do not display any dominant frequencies, Fig. 4, which indicates that the presence of the ring suppresses the formation of large-scale structures in the mixing layer.

References

3. H. Sadeghi and A. Pollard, “Experimental study of the development region of a turbulent round free jet under flow modifications near the exit: case 1: shear layer modification, case 2: potential core modification,”
Evaluation of CFD Prediction of Drag Force over a Cowled Ejector
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Synopsis
In predicting the drag force exerted over an ejecting device within a streamlined cowling, it has been found that the CFD does not provide accurate results. Both CFD and experimental analysis of a cowled ejector geometry are undertaken to evaluate the drag prediction abilities of CFD.

Introduction
An ejector is a device that is used to mix the exhaust from a gas turbine aeroengine with ambient air in order to increase thrust, decrease noise, and improve efficiency. The addition of one of these devices can also decrease performance by increasing drag over the engine and back pressure. CFD software does not accurately predict the drag force exerted on the devices, causing device performance to not be as expected, and means that costly scale testing must be undergone on each prototype.

Methods
In order to determine the greatest accuracy that can be expected from CFD analysis, an ejector with a four ring entraining diffuser and streamlined cowling were designed to undergo both CFD modelling and full scale testing.

Two methods of calculating the drag are examined for accuracy. The near-field technique uses the integration of the pressure on shear forces acting on the object’s surface, while the wake integration method calculates the momentum losses over an object using measurements from the wake behind the object. It has been found that the wake integration method can provide more accurate drag prediction than the near-field technique [1].

A CFD model of the designed geometry is created and used to simulate flow around the model, and both drag calculation techniques are used to find the drag force acting on the model.

Conclusions/Continuing Work
In order to determine the accuracy of the CFD modelling, the ejector and cowling will be manufactured and tested in a low speed wind tunnel to replicate the CFD conditions. The drag over the device will be measured using the wake integration method and through the use of a simple axial force balance.

References
Synopsis
The use of multi-phase explosives is becoming more common and little is known about the dense gas-solid flow that occurs after the initial detonation.

Introduction
The study of particle cloud dispersion by a shock wave is important to many applications, including multiphase explosives that comprise a condensed explosive surrounded with packed micrometric reactive metal particles. Detonation of the explosive generates a shock wave which accelerates and compacts the particles. The particles are further accelerated from the reflected rarefaction as the shock wave arrives at the free-surface of the particles, leading to their rapid dispersal into the air. Generally speaking, the shock wave initially propagates through a granular particle bed and much later in time the particle cloud is dispersed and the flow becomes a dilute gas-solid flow. Between these two regimes the flow is characterized by a dense gas-solid flow [1]. Reactive multiphase flow models have been used to simulate the acceleration and dispersion of the particle cloud [2]. The fidelity of the simulations is severely limited by the physical drag models that need to take into account the interactions in the dense gas-solid flow [1]. In order to develop an accurate particle drag model that describes particle acceleration in the dense flow regime, representative experimental data need to be generated. While dispersal experiments have been carried out using a spherical multiphase explosive charge [3], controlled shock wave experiments are necessary to gain understanding of the fundamental physics of the dense supersonic gas-solid flow interactions and quantitative data concerning the particle cloud dispersion. Shock tube experiments have been carried out but typically the particle suspension method influences the shock flow [2] and the particle size is not typical of multiphase explosives. This paper reports on shock tube experiments looking at the acceleration and dispersion of 100 micron-sized aluminum oxide particles. The shock wave propagating into the packed particles provides a low-pressure analogy to multiphase explosive dispersal.

Method and Results
This paper reports on shock tube experiments looking at the acceleration and dispersion of 100 micron-sized aluminum oxide particles. The novelty of the experiment is that there is no obstruction of the blast wave flow by a particle cloud supply structure. Before the experiment the particles are compressed into a 6 mm thick wafer. The wafer has just enough strength to be able to position it vertically in the horizontally oriented shock tube, however it crumbles with very little force. The wafer fills the cross-section of the tube and is positioned 84 cm downstream from the diaphragm. Thus, the shock wave propagating into the packed particles in the wafer provides a low pressure analogy to the multiphase explosive dispersal. Pressure transducers located before and after the wafer are used to record the incident, reflected, and transmitted shock wave pressure. The shock tube driver section is 2 m long with a 7.6 cm diameter cross-section and the driven section is 7.6 cm square and 3.6 m long. A double diaphragm, located before a transition section, is used to precisely control the shock Mach number. A high-speed shadowgraph video system is used to track the front and back edges of the particle cloud following the interaction of the incident shock wave and the wafer, as seen in Figure 3. The pressure recorded at six axial positions in the shock tube and the shock and cloud trajectory for a Mach 2.0 shock wave is provided in Figure 4.

Conclusions and Future Work
While the front particles are initially dispersed through the reflected expansion upon the transmission into air, the clear finding here is that the reflected shock generates in the back of the granular bed a pressure pulse that is the driving force to maintain the forward motion of the all the particles. Tests will be conducted with thicker wafers to gain insight into the correlations of the pressure wave structure with the granular bed thickness. The obtained transition phenomena and wave structure will be used to validate the constitutive relations and drag model used in numerical modeling.

References
Detonation cell Size Data for Dimethyl-ether Air Mixtures

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Synopsis
Dimethyl-ether (C₂H₆O) a common hydrocarbon is increasingly being used as a transportation fuel and as an aerosol propellant, very limited explosion safety data is available for this fuel. Experiments were performed to determine the detonation characteristics of dimethyl-ether air mixtures as a function of composition, initial temperature and combustion initiation.

Introduction
Dimethyl-ether is currently used primarily as an aerosol propellant in the place of CFC propellants and as a replacement for propane in liquefied petroleum gas (LPG). There is increasingly more interest in dimethyl-ether as a transportation fuel. Because of its high cetane number and very low emissions during combustion it is especially well suited for compression ignition engine applications. As these applications are developed an infrastructure to transport and store the fuel will have to be developed. Or alternatively, expand the existing infrastructure currently used for propane which has similar properties. Very little explosion safety data is currently available for DME. Mogi et al. [1] performed experiments in two different combustion tubes where they measured detonation velocity and pressure for DME-air mixtures at atmospheric pressure and temperature within the detonability limits. Ng et al. [2] measured the detonation cell size of DME-oxygen mixtures at 298K. They observed a multi-cellular detonation structure for all compositions at low initial pressure. This paper reports experimental results for DME-air mixtures at 298K and 373K.

Methods and Results
Experiments were performed in a 6.2m long, 10cm inner-diameter heated detonation tube, as seen in figure 1, to determine the detonation characteristics of dimethyl-ether (DME) air mixtures. The detonation velocity and pressure were measured, and cell size was obtained using the soot foil technique. Modeling of equilibrium detonation characteristics were carried out along with kinetic modeling of the steady one-dimensional detonation structure to compare with experimental detonation properties. The measured detonations velocities closely match the calculated Chapman-Jouget (CJ) detonation values. DME-air detonations showed a double-cell pattern for all compositions as seen in figure 2. From the kinetic modeling it is evident that DME-air detonations undergo two-stage heat release, on the fuel rich side, as seen in figure 3, which explains the double cell pattern observed. The detonation composition limits were found to be slightly wider at 373K then at 298K which is contributed to the decrease in the size of the large scale detonation cells.

Future Work
A gas driver ignition system has recently been added to the end of the detonation tube to allow for detonation initiation with a shortened orifice plate array. The shortening of the orifice plate array should allow for a broader range of mixture compositions to be tested in the current detonation tube by increasing the effective diameter of the tube from the orifice plate diameter to the tube diameter.

References
Thermoelectric Heat Pump: Characterization of Performance in Heating Mode
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Synopsis
Domestic hot water (DHW) makes up a significant portion of Canada’s residential energy consumption. Thermoelectric heat pumps could provide an alternative attractive to direct electric heating for DHW, however current research focuses primarily on their use in cooling and electricity generation. A model was developed in TRNSYS to predict the performance of a thermoelectric heater and a calorimeter was constructed for validation. Performance measurements and simulation results will identify key design parameters for optimized thermoelectric heating systems.

Introduction
Domestic hot water makes up 22% of residential energy use [1]. Electricity and natural gas are the two major fuel sources for water heating in Canada, making up 45.2% and 49.6% of the market respectively [2]. Reducing the energy consumption of domestic water heaters could therefore provide significant environmental benefits. Heat pumps can appreciably improve the energy performance of water heating when compared to direct electric heating, however current vapour compression systems are expensive to purchase and maintain [3][4]. Recent improvements in thermoelectric module (TEM) performance [5] could make them an attractive alternative to vapour compression systems but very little research has been conducted to evaluate TEM performance in heating mode. An investigation has been undertaken to model the performance of commercially available TEMs in heating mode and develop a robust TRNSYS model which may be used for further systems design. This paper presents some initial empirical results and a model of a simple TEM heater.

Methods and Results
Commercially available TEMs were characterized using a custom built calorimeter as shown in Fig. 1 and 5. Four thermoelectric modules were wired in series and “sandwiched” between two lapped isothermal copper plates with embedded thermocouples. Hot and cold sides were compressed against simple liquid driven heat sinks with minimal contact resistance. The Seebeck coefficient, thermal conductivity, and internal resistance of the modules were measured to develop a semi-empirical model of the TEMs performance. The Thomson effect can be assumed to be negligible for initial calculations [6]. Figure 3 shows predicted COPs using these key parameters which closely follow the values provided by the manufacturer. Larger discrepancies at low temperature differences suggest the Seebeck coefficient temperature dependence may be significant. A software “component” model was created in TRNSYS to simulate the operation of a thermoelectric heater given manufacturer specifications. Performance results are shown in Figure 4 for a simple thermoelectric water heater with varying heat sink U-values.

Future Work
Preliminary results show that the semi-empirical model provides a close match to manufacturer specifications. A TRNSYS “component” was created which suggests average COPs of 1.65 can be obtained with a simple thermoelectric DHW system. The temperature dependence of key parameters will be determined and integrated into the TRNSYS model. Direct measurements of the COP using the calorimeter will be used to determine the true performance of the thermoelectric heater in operating conditions predicted by the model. This will include an investigation into the performance of the TEMs under negative temperature gradients. A sensitivity analysis will determine key areas for optimization of TEM heaters for DHW.

References
Large eddy simulation of boundary layer/wall jet with embedded spanwise vortices
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Synopsis
When helicopters land or hover near the ground, the wake of rotor forms a downward-directed jets spreading radially as it reaches the ground, with coherent helical vortices generated at the blade tip embedded within it. The interaction between the impinging wall jet and the blade-tip vortices is of great interest especially when particles such as sand or snow on the ground exists. It was reported that unclear pilot's view caused by liftup of those sediments resulted in significant loss of life and damage to rotorcraft[1]. Numerical simulation of this flow field could allow for the investigation of interaction between down-wash spanwise vortices and near wall flow structures and help to optimize liftup of sediment.

Introduction
Experimental and numerical studies have been carried out. Johnson[2] and Kiger performed laboratory scale experiments on interactions between rotor-wake/impinging jet and vortices. The real case is rather complicated for numerical simulation due to high Reynolds number (up to 10^6) and combination of progresses: generation of blade-tip vortices, development of impinging jet and interaction between fluid and solid particles. Simplified lower Re case using jet fields data as boundary conditions and artificial imposed vortices is easier to carried out and studied at the beginning stage. Fluid-solid coupling simulation about particles will not be considered before features of flow field has been carefully investigated. Naqvi and Piomelli[3] performed large eddy simulation of putting spanwise vortices into turbulent boundary layer to figure out the change of vortices structure and its influence on boundary layer statistics. Work presented here follows their researches and uses wall jet which is more close to the real case instead of boundary layer. Radical spreading nature of the jet is also taken into consideration in this case.

Methods and Results
Different cases are carried out under Cartesian and cylindrical coordinates with boundary layer or wall jet being the near wall structure to be involved. Parallelized finite difference code is used for numerical solving of Navier-Stokes equation and spanwise vortices are impulsively imposed periodically by adding forcing term to N-S equation with Immersed Boundary Methods (IBMs). Parameters of vortex normalized by mean velocity fields values are obtained from experimental data provided by Kiger. Figure 1 is the profile of tangential velocity of vortex as a function of radius. The core of vortex is like a rigid body rotation and the outer layer is very close to irrotational vortex. Figure 2 is instantaneous Q isosurface of Cartesian wall jet case at the 3/4 phase. It could be seen that near wall structures are enrolled by the vortices impinging to the wall. Figure 3 shows the spanwise averaged instantaneous fields of spanwise vorticity of Cylindrical wall jet case at the 3/4 phase.

Figure 1. Profile of tangential velocity of vortex and Volume Of Fluid as functions of \( r/\rho \)

Figure 2. Instantaneous Q isosurface of Cartesian wall jet case at the 3/4 phase

Figure 3. Spanwise-averaged instantaneous spanwise vorticity fields of Cylindrical wall jet case at the 3/4 phase.

Conclusions
Compared with the boundary layer cases, the Cartesian coordinate wall jet cases are more close to real flow. It shows that the spanwise vortices were impinging into the wall jet and rolling near wall structures. Cylindrical coordinate cases well present the effect of radical spreading and expansion effect as the result of it. Further study will focus on the effect of different runtime parameters such as Reynolds number, downwash velocity, time interval between vortex releasing and so on.

References
Student Perspectives on Engineering Design Education – A Work in Progress
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Introduction
It is widely recognized by industry and academia that design is the central creative activity in the engineering profession. Contemporary research literature in engineering education identifies the need for design education to prepare holistic engineers with the knowledge, skills, and attitudes to innovate and compete globally. Engineering accreditation boards in both the United States and Canada recognize the importance of design in their use of an outcomes-based approach to engineering accreditation. To meet these interests from industry and academia, and to enhance the development of future engineering students, it is important to advance the teaching and learning of engineering design. This paper discusses a work in progress of research that aims to understand students’ thinking about design by looking at the meaning students assign to design in the engineering context. By considering undergraduate engineering students’ conceptions of learning and practicing design, engineering educators can optimize curriculum and learning experiences accordingly.

Learning Theory
The field of educational psychology provides the background in the learning sciences to understand how learning works. In the same way civil engineers apply statics and mechanics to design a bridge, engineering educators should apply the science of learning to design engineering curriculum and enact effective teaching strategies. Therefore, it is the aim of this research to apply the knowledge of how learning works to advance the design of engineering curriculum and teaching. The concepts from the science of learning that are applicable to this research are discussed below.

Transfer of Learning
Transfer of learning, defined as “the effect of prior learning on new learning or performance”1, is concerned with the ability of a learner to apply what he or she has learned in one context to a new situation. The nature of engineering design is fundamentally a transfer of learning challenge, because it requires students to apply their knowledge and skills to solve complex, ill-defined, open-ended problems. To aid students in the ability to transfer their learning, it is important to understand students’ prior knowledge.

Prior Knowledge and Knowledge Organization
Engineering design involves the interplay of two types of knowledge: declarative and procedural. Declarative knowledge is defined as “the facts and concepts that can be stated or declared” and procedural knowledge involves “knowing how and knowing when to apply various procedures, methods, theories, styles, or approaches”2. Prior knowledge plays a significant role in learning because “students connect what they learn to what they already know”3. Prior knowledge also promotes learning when it is activated, sufficient, appropriate, and accurate3. In this way, understanding how students think about design will provide insight to engineering educators when teaching and designing curriculum to promote transfer of learning. Learning theory further posits that “how students cognitively organize knowledge influences how they learn and apply what they know”4. Therefore, educators should strive to go beyond just teaching the content of a particular subject, and make explicit how they structure knowledge and the thought processes behind using that knowledge.

Metacognition
Metacognition plays a significant role in understanding how students think about and approach their learning. Metacognition in learning is used to describe the awareness and control of one’s cognitive processing—that is, thinking about one’s thinking. Metacognition is a critical skill for design and is directly linked to the promotion of self-regulation, an attribute of lifelong learning. If engineering educators are to promote metacognitive thinking, an understanding of students’ current cognitive awareness is necessary.

Research on Students’ Attitudes
This research serves to bridge the research-to-teaching gap by applying the science of learning to influence design education. Several studies point to the importance of understanding students’ perceptions of engineering education and the role these perceptions have on engineering recruitment, retention, and performance3. The study by Downey and Lucena investigated “how students understand the distinction between ‘science’ and ‘design’”4 and found that students hold negative perceptions toward design. The study suggests that curriculum reform to shape students’ attitudes is necessary from both an engineering science and design perspective.

There are a number of valid instruments to measure various affective traits of students5. However, since these instruments are quantitative in nature and focus on assessment, there is a need for qualitative inquiry that provides detailed description of the underlying factors contributing to the affective results. This approach is evident in the qualitative study by Matusovich, Streveler, and Miller6, who use Expectancy-value theory as the framework to measure and describe students’ motivational values towards pursuing engineering. From the science of learning and the previous studies on affective traits of engineering students, it is evident that understanding students’ attitudes towards learning design will help engineering educators teach design and develop engineering curriculum.

Method
A one-time online questionnaire is in the process of being distributed to first, third, and fourth year undergraduate engineering students at three Canadian institutions. In the questionnaire, students are asked to reflect on their experiences of learning and practicing design and describe what engineering means to them. The student responses will be qualitatively analyzed to generate themes of meaning from the students’ descriptions. Semi-structured interviews with select students will also be conducted to gain a deeper understanding of students’ experiences with engineering design.

Discussion
This research serves to advance the understanding of undergraduate engineering students’ conceptions and beliefs towards learning and practicing design. With an understanding of how students learn and think about design, engineering educators may be better prepared to optimize curriculum development and instructional strategies. The results of this research also hold direct implications for engineering recruitment and retention by providing educators with a deeper understanding of the engineering student experience.

References
Fuzzy Adaptive PID Position Control of a Pneumatic Gantry Robot
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Synopsis
Considerable research has been conducted on the control of pneumatic systems. However, nonlinearities continue to limit their performance. To compensate, advanced nonlinear and adaptive control strategies can be used. But the more successful advanced strategies typically need a mathematical model of the system to be controlled. This research reports on a study whose objective is to explore the potential of non-model-based compensators for nonlinear behaviors for the position control of a pneumatic gantry robot. It was found that a novel fuzzy adaptive PID controller could improve tracking performance on the order of 45% to 70%, equal to that achieved by an adaptive neural network compensator (ANNC) as developed by a previous Masters student [1]. This level of performance was obtained only after careful tuning of both methods. The presentation sets out to document the fuzzy adaptive PID algorithm and presents experimental results that illustrate its adaptive nature and compares performance with PID+ANN.

Introduction
Pneumatic servo systems are attractive for control applications where there is a need for lower installed cost, longer working life, continuous duty cycles or reduced risk of explosion. But the problem with pneumatics is that their accuracy is low relative to electric and hydraulic actuators. A large body of research is devoted to the application of advanced control techniques to servo pneumatics in order to improve their performance [2]. As one source of nonlinearity, friction can have a significant effect on tracking performance, especially in applications that use rodless cylinders which have higher Coulomb friction than rodded cylinders. Many friction compensation techniques are model based. Although they show relatively good results, the requirement for a system model can make these methods difficult to implement. For this reason, “intelligent” algorithms such as neural networks and fuzzy rule based controllers that don’t use system models are attractive. Adding an adaptive feature can improve performance still further, where the controller gains are constantly updated to account for changes in operating conditions and system parameters.

Methods and Results
The fuzzy adaptive PID controller is the fuzzy version of the traditional PID. It requires knowledge of the nature of the PID gains to implement the fuzzy membership functions and fuzzy rules. These variable PID controller gains are adjusted on-line with a set of fuzzy rules. The block diagram for the controller and the experimental setup are illustrated in the following figure. This method benefits from the inherent robustness of PID and the adaptive action of the fuzzy algorithm. In this research, the proposed method uses a novel rule set that is reduced in size and modified from that used in previous studies. It was based on a series of trial and error tests, which confirmed that linking the PID gains to the terms they are most dependent upon, would result in better adaptation. Tests were conducted on both rodless and rodded cylinders. The best result achieved was an average absolute error of 0.9 mm for the rodded cylinder, which corresponds to 0.75% of stroke. The best result for the rodless cylinder was an error of 8.0 mm, which is equivalent to 0.80% of stroke.

Conclusion
The main conclusion of this work is that both fuzzy adaptive PID and PID + ANNC methods can significantly improve tracking performance. Improvement is expected given the adaptive nature of both methods. A major contribution of this study is demonstration that a novel fuzzy rule set that is reduced in size with rules modified from those used in previous studies, can improve performance and reduce the computation overhead of the control algorithm. Work continues with a view to develop an autotuner for both the ANNC and adaptive fuzzy PID algorithms. The autotuner would be used to reduce the amount of effort required to setup the controllers and adapt to changing initial conditions such as supply pressure, setpoint tracking frequency and payload mass.

References
Fixed Beam Laser Welding of Alumina Ceramic Plates
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Introduction
Engineering ceramics have a number of qualities which make them useful in a variety of applications: they have high hardness and melting temperatures, and are excellent thermal and electrical insulators. The joining of ceramics is typically achieved through mechanical fastening, brazing, or bonding with specialty adhesives. Welding ceramics is advantageous over these traditional methods however, as it allows for consistency in mechanical properties across the joint and does not introduce impurities into the assembly. Successful welds have been formed in alumina using lasers. Studies have shown that preheating the ceramic prior to welding is necessary to prevent the formation of cracks from the high thermal gradients formed during the welding operation [1, 2]. Lasers have been used for both preheating and welding [2]. This work investigates the use of a fixed defocused laser beam for preheating, followed by a second focused beam for welding. This method reduces the complexity and cost of the manufacturing process as it eliminates the scanning system employed by other methods.

Methods and Results
A protocol is being developed that involves the use of a 250W CO$_2$ laser and a 100W Nd:YAG laser for welding alumina plates. Both beams are fixed and arranged at a defined offset. The CO$_2$ beam is defocused to allow a large area to be preheated, while the Nd:YAG laser is focused to melt and fuse the ceramic. The ceramic is held in a fixture which moves at a constant speed under the laser beams to complete the weld (Figure 1). Tests will be performed at different degrees of defocusing to vary the induced temperature gradient. Temperatures will be monitored with a pyrometer. Cross sections of the weld will be observed for porosity, and the strength of the joint will be compared to that of a solid specimen using a four-point bend test. Knife edge tests have been performed to determine beam diameters at different defocusing levels (Figure 2). A Finite Element Model (FEM) of the preheating process is being developed in COMSOL MultiPhysics to aid in determining initial testing parameters.

Conclusions
A protocol is being developed for the laser welding of alumina ceramic plates using a dual beam method; a 250W CO$_2$ beam laser will be defocused to preheat the ceramic plates along the seam followed by a focused 100W Nd:YAG laser to complete the weld. An FEM is being developed to aid in determining initial parameters. The success of the welds will be determined through inspection of cross-sections for porosity, and a four-point bend test for joint strength.

References
Electrically Assisted Single Point Incremental Forming
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Synopsis
Single Point Incremental Forming (SPIF) is a relatively new method of die-less sheet metal forming that allows custom and low production runs of complex sheet metal parts to be made for very low cost per part. SPIF works by replacing the milling cutter with a solid, round forming tool and using a CNC mill to form sheets. Electrically Assisted Manufacturing (EAM) is a method of improving the forming limits of metals by introducing a material to extremely high DC current during forming. A method of introducing EAM to SPIF is proposed, with the goal of expanding to capabilities of SPIF to include exotic materials such as Titanium alloys.

Introduction
Single Point Incremental Forming is a highly capable process, which can be used to form a variety of very complicated sheet metal parts with no specialized tooling such as dies. The main limitations of SPIF, however, are a lack of tolerance predictability due to springback, and wall angle limitations. In particular these limitations are very restrictive while forming Titanium and Magnesium alloys. Some methods have been applied to improve the formability such as warm forming [1], laser assisted heating [2] and electric heating through the tool [3]. Electrically Assisted Manufacturing (EAM) is a method of improving the formability of metals by passing very high current electricity through the part during forming. The formability increase has been shown to be much greater than predicted by simple joule heating [4]. It is proposed that it could be possible to extend the capabilities of electrically assisted SPIF past that of Guoqiang's work [3] by cooling the sheet, allowing for even higher currents to be passed through the sheet and thus further improving the forming limits.

Methods and Results
An apparatus (shown in Figures 1 and 3) has been designed to safely carry very high currents from a power supply (a) to a rotating tool (b) via a slip ring (c). The rotating tool is then used to form a sheet (d), which is held on a blankholder (e). The power supply is a Magna Power TSA5-900, capable of delivering up to 900ADC continuously to the tool. Forming performance will be determined by forming a part of variable wall angle, and determining the wall angle that breaks the part. To remove the element of heating in the sheet, two methods will be attempted: cooling the sheet using compressed air, and reducing the heat load by using pulsed current.

Currently, the apparatus is in the process of being built, with only the wiring to be finalized. Pending the approval of the Electrical Safety Authority, electrical tests can begin shortly.

Conclusions and Future Work
From similar work [3] it has been showing that applying current to the part through the tool can greatly improve the forming limits of SPIF parts and allow for exotic materials to be formed. It has also been shown that EAM can greatly improve the forming limits of metals, and can do so without the need for high temperatures [4]. Combining these will allow for rapid custom forming of complicated, strong lightweight parts. Specific areas to investigate in future will be the effects of additional cooling such as through tool air cooling, and the effects of tool shape and changing conductivity to control the electrical contact patch.

References
Optimization Tool Development for Pack-Level Electric Vehicle Battery Cooling
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Synopsis
With increasing interest in the electrification of personal transportation the creation of safer and more efficient battery technologies has become a major interest for auto makers. The ever increasing energy densities of current battery technologies and their dependence on temperature mean that a well designed thermal management system is required to maintain the proper temperature of EV batteries for safety and efficiency. Since EVs and the associated batteries are a relatively new field of research seeing continuous development the application of design optimization to the thermal management system will aid in the design process and reduce development cost of new designs.

Introduction
The most popular battery type being used to day for EVs is the Lithium-Ion (Li-Ion) battery. It offers significant advantages over previous battery chemistries such as Nickel-Metal Hydride (NMH) and Lead-Acid (LA) in terms of efficiency and amount of energy storage. Temperature dependence in these types of batteries is a complex problem with competing variables and effects; Heat generation comes from 2 different sources, joule heating due to the current passing through the battery as well as heat generated due to the chemical reaction taking place within the battery. Decreased temperature is advantageous for the joule heating effect however too low a temperature can slow the chemical reaction reducing the power output of the battery. With increased temperature the chemical reaction proceeds more quickly but permanent damage to the battery can occur due to unwanted reactions. Along with the efficiency of the battery with respect to its power output the lifetime of the battery pack must also be considered. With a substantial replacement cost any battery pack intended for commercial applications must have a long (10+ year) lifetime. These competing effects on efficiency, power generation as well as lifetime make EV battery pack thermal management systems an ideal candidate for the development of multi-disciplinary optimization tools for future designs.

Methods and Results
Optimization of the battery pack thermal management system will be performed on a finite element model (FEM) of the battery cells and associated cooling hardware. Heat generation within the battery cells is being modeled using non-uniform heat generation which is affected by the location within the cell. The cooling provided by liquid-cooled plates is being modeled as a negative heat generation within the plates and will be tuned to reflect work done on the plates themselves previously [1].

Initially the analysis will be steady state, a time dependent model with loads based off standard drive cycles being the final goal. In the time dependent model factors such as vehicle mass, air drag and rolling resistance will be included. This analysis will show the temperature distribution within the battery pack not only spatially but also with respect to time. With highly anisotropic material properties and complex factors affecting internal heat generation, the results of the analysis will highlight which areas are of highest importance for any given battery cell.

Conclusions
This optimization and development tool will aid in identifying areas of concern for new battery technologies while still in the design phase. It also allows for the comparison of different cooling methodologies (such as air, liquid etc.) as well as combinations of approaches. With newer and higher energy density batteries being continuously developed identifying the optimum arrangement for the thermal management system is of great importance.

References
Reducing the Effects of MRI Acoustic Noise using Micro-Perforated Panels
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Synopsis
Magnetic Resonance Imaging (MRI) can create very high levels of acoustic noise. One proven way to reduce this noise is to install a micro-perforated acoustic absorber panel inside the bore of the scanner. The effectiveness of a previously designed micro-perforated panel was measured during a cognitive neuroscience functional MRI (fMRI) study. Preliminary results confirm that panels decrease measured noise inside scanner bore and that 33% of volunteers noticed a decrease in scanner noise with panels in.

Introduction
Magnetic resonance imaging (MRI) has revolutionized the field of cognitive neuroscience as it allows researchers to noninvasively map brain function in response to stimulus or task demands. However, the acquisition of MR images generates substantial acoustic noise, making studies of speech, language and hearing problematic.

Installing micro-perforated panels inside the bore of the scanner has been shown to reduce the acoustic noise transmitted into the bore of the magnet[1]. Although these panels result in quantifiably lower noise levels, measured with microphones in an empty MRI, the improvement has not been quantified with a person in the scanner bore, which dramatically affects the acoustic noise field.

Materials and Methods
An auditory functional MRI study, incorporating both periods of auditory stimulus presentation (plus scanner noise), and periods of scanner noise alone has been carried out. Thirty individuals were scanned, twice each: once with acoustic absorber present, and once absorber absent in counterbalanced order. The difference in auditory brain response between the experimental stimulus and the scanner-noise-alone epochs will be measured, and compared between the absorber present and absorber absent conditions. The degree to which the brain response differs between these two conditions indexes the improvement due to the absorber panel. This measure will provide a way to systematically compare the attenuating qualities of panels in a realistic application mode.

The improvement due to the absorber panels has also been indexed by recording acoustic noise next to the subject’s head to confirm that lower levels of noise were being emitted from the scanner. Additionally volunteers were asked to rate the scanner noise they perceived to see if a noticeable improvement was made.

![Figure 1: Reduction in MRI acoustic noise due to micro-perforated acoustic absorber panels](image)

Conclusions/Future Work
Preliminary results from microphone measurements confirm that panels reduce scanner noise as shown in Figure 1. Additionally 33% of volunteers noticed a decrease in scanner noise with panels in. Continued analysis of fMRI and acoustic measurement data remain to determine effectiveness of acoustic absorber panels.

References
Synopsis

Robots have moved from reachable environments of laboratories and factories into the hazardous or remote environments in order to reduce the time, cost and risk involved in enabling humans to endure these conditions. The fault in a manipulator can be defined as any event in the system that degrades the performance of the manipulator, and as a result the manipulator becomes unable to perform its assigned task properly. A manipulator is fault tolerant if once one of the subsystems fails, the reduced manipulator still is capable of accomplishing its mission objective. In the proposed research, the failure recovery for force/moment (wrench) and velocity (twist) capabilities of parallel manipulators is investigated. A failure recovery methodology based on partitioning the mobile platform task space into the major and secondary subtasks, [1], is presented in order to accomplish the major subtask while optimizing the secondary goals.

Introduction

Manipulators can be classified based on their kinematic layout. A manipulator is said to be a serial manipulator if its kinematic layout takes the form of an open-loop chain of links connected by joints from the base to the mobile platform. Solid-link parallel manipulators, Figure 1, are closed-loop mechanisms in which the mobile platform is generally connected to the base platform using a number of kinematic chains of links and joints. Wire-actuated parallel manipulators, Figure 2, are a special type of parallel manipulators in which the solid-link legs are replaced by wires. That is, in this type of manipulators the position and orientation of the mobile platform are controlled via wires.

Faults of parallel manipulators are analyzed at the component level (link and joint fault), subsystem level (branch and mobile platform fault), and system level (parallel device fault). If any of these faults affect the performance of the manipulator so that the required task cannot be accomplished, then the manipulator is failed. The system reliability and fault tolerance could be improved through redundancy. Incorporation of redundancy into design is one of the popular approaches in fault tolerant manipulators. Redundancy includes actuation redundancy, kinematic redundancy and task space redundancy. In the task space redundancy, most complicated tasks given to a manipulator can be formulated in such a way that the task is broken down into several subtasks with a priority order. Then the task space is divided into the major and secondary tasks according to their importance in order to complete the major task and optimize secondary goals. One of the main challenges is that in redundant manipulators, for a given platform wrench, an infinite number of actuator torques/forces exists. Hence, selecting a unique solution among the infinite solutions is complicated and requires several considerations such as minimizing actuator forces/torques, reliability enhancement, singularity avoidance, obstacle avoidance, optimizing fault tolerant measures and joint limit avoidance.

Methods and Results

To provide failure recovery in parallel manipulators, redundant degree of freedom is taken into account in each leg of the manipulators. When a parallel manipulator has a failure in joint 6 on leg i, its joint velocity will be different than the required value. The Jacobian matrix after the failure is reduced such that the column corresponding to the failed joint(s) is replaced by zero. When the projection of the required twist onto the orthogonal complement of the range space of the reduced Jacobian matrix of the leg with failed joint(s) is not a null vector, the lost motion would not be completely recovered. Instead, only the components of the resultant vector that may have zero entry would be recovered.

In many applications some subtasks are very crucial and must be controlled as precisely as possible. Other subtasks are less important and can be considered as redundant and their tracking performance can be compromised to achieve useful performance criteria. In this research, based on the kinematics and static force model, the velocity and static force projections are formulated. The components of the twist/wrench vector, expressed as major degree of freedom, MDOFs, are accomplished and at the same time the secondary goals, SDOF, are optimally completed. The common joint/actuator failures, e.g., locked joint failure and free swinging failure are investigated. To verify results, simulations are performed on a planar solid-link parallel manipulator in Figure 1 based on differential kinematic model. By choosing some components of the twist as MDOFs and the remaining ones as the SDOFs, the Jacobian matrices corresponding to MDOFs and SDOFs are obtained. The weighted generalized inverse of the Jacobian matrix corresponding to the MDOFs is used to solve for correctional joint velocities of the remaining healthy joints. The velocity of the remaining joints is adjusted such that the desired MDOFs are achieved and simultaneously the 2-norm error of the required SDOFs is minimized. Table 1 shows the simulation results. In case 1 for the platform twist $\mathbf{V} = [1.0 \ 0.2 \ 0.873]^T$, failure in the first joint has no effect in the motion capability of the manipulator. In case 2 when both passive revolute joints are jammed, the two prismatic joints can retrieve the linear velocity of the mobile platform. However, it cannot recover the lost angular velocity. In case 3, following the failure of the first two joints, just angular velocity of the mobile platform could be retrieved.

Conclusions

The differential kinematic and static force models of general manipulators were calculated. The effect of one or more failed joints on the twist capabilities of parallel manipulators was studied. To deal with the failure in joints/wires, the kinematic redundancy as well as actuation redundancy were incorporated in the manipulator architecture. The methodology was based on the projection of the lost joint velocity onto the orthogonal complement of the null space of the reduced Jacobian matrix after the joint failure in order to calculate the correctional input provided by the remaining healthy joints/wires. Conditions in [2] were used to examine if the lost mobile platform twist could be fully or partially recovered. A similar methodology was used to retrieve the lost mobile platform wrench due to zero/limited joint forces/torques.

References

Introduction and Motivation

The goal to minimize emissions and lower operating costs by monitoring and controlling fuel efficiency has been a growing concern around world, and the mining and construction industries are no exception (1). My project is a subproject of the Mine Traffic Optimization (MTO) project and is funded by MITACS and Barrick Gold Corporation. One objective of the MTO project is to examine how mine traffic affects fuel efficiency. At a broader scale, the MTO project also seeks to examine ways to maximize production, increase operating efficiency and maintain safety while minimizing costs and environmental impacts of hauling.

The largest single contributor to energy consumption in open pit mining operations is haul trucks, which accounts for about 67% of fuel used in 2010 at Goldstrike mine (2). By examining haul trucks in their operating environment, strategic changes in critical parts of the truck cycles could result in significant fuel savings. Monitoring the trucks real time operating parameters allows us to consider different ways for modifying trucks behaviours in order to reduce overall operating costs. This presentation presents some of the preliminary analysis done in order to achieve this last objective.

Objective and Methodology

320 ton hauls trucks (Figure 2) at Goldstrike mine were equipped with monitoring equipment (Figure 3) and were asked to perform under normal operating conditions in order for data extraction. There are 2 primary objectives within this study. The first objective is to examine haul truck behaviour on different grades in order to establish a potential mine forecasting tool. The second objective is to monitor the impact of intersection on haul trucks and examine impact on fuel and operation efficiency. Beyond the primary objectives a third objective was to observe dumping behaviours in order to see potentials for fuel savings. Each of these aspects are key components of the hauling process (Figure 1) and each can result in fuel inefficiencies.

Figure 1: Haulage Cycle Breakdown

Project Status and Future Work

All data has been gathered from the summer of 2011 thanks to Barrick Goldstrike mine in Elko Nevada. An analysis of the secondary objective has been completed, examining different performance parameters (RPM, fuel consumption) and performing a sensitivity analysis (fuel price, gold price) to outline fuel savings. Overall, dumping which accounts for 3.5% of the haulage cycle resulted in over $6000/year savings per truck. This analysis will be used as a baseline for developing the primary objectives, which focuses on 80% of the haulage cycle. The primary objectives required coding and restructuring in order to begin analysis, and should be complete by late November.

Dependence of the Local Texture, Defect Structure and Chemistry on the Annealing Response of an AA6XXX/A3003 Clad System
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Synopsis
Throughout the last decade consumer concerns about the environment and potential new government legislation have finally pushed the automotive industry to a realization to increase the fuel efficiency and performance of their production line vehicles. With combustion engines reaching maximum efficiencies the best method to achieve large increases in fuel economy is through weight reduction by switching from conventional steel frames and body panels to aluminium, which has a density three times lower. The aluminium industry has simultaneously being developing specialized alloys and products for automotive use, but they have not made great penetration into the auto market beyond high-end production vehicles due to limits in ductility, surface aesthetics, and cost.

Introduction
Novelis Inc.’s Fusion Technology is an aluminium casting method for producing multi-layered direct chill ingot slabs. These ingots are then rolled into sheets of an aluminium cladding system with a perfect metallurgical bond between layers. The customized products can be tailored for increased corrosion resistance, bendability, and brazability. The bonded interface however allows for some interesting chemical, mechanical and textural properties. It has been hypothesized that this is due partly to the ability of diffusion across the interface along and partly because of the heterogeneous straining occurring between the core and clad microstructure. The results are different texture and defect structures between the two alloys resulting in rapid recrystallization throughout the inter-alloy region during a continuous heat treatment and anneal (CASH). Therefore to insure this predictability it has been necessary to understand the evolution of this inter-alloy region, during cold working, recovery and recrystallization.

Results and Methodology
Instrumented indentation with rate changes and chemistry measurements have been conducted across the inter-alloy region after rolling and subsequent annealing. Traversing from the core to clad alloy side showed a large decrease in hardness, with a maxima and minima close to the visible interface in the 6XXX and 3003 series respectively. The local chemistry was then measured across the inter-alloy region using energy dispersive x-ray spectroscopy taken next to each indent, or continuously through the thickness using glow discharge optical emission spectroscopy (GOES). As seen in Figure 1 a large inter-alloy region of approximately 30μm was observed, where inter-diffusion occurs. The alloys chemistry was then related to the measured activation volume via strain rate sensitivity measurements taken during the hardness measurements.

![Chemistry across the as-rolled clad-core inter-alloy region, EDX points, GOES: lines](image1)

Fig. 1: Chemistry across the as-rolled clad-core inter-alloy region, EDX points, GOES: lines

![Apparent activation volume (V') dependence upon two chemical elements at point of recrystallization](image2)

Fig. 2: Apparent activation volume (V') dependence upon two chemical elements at point of recrystallization.

After cold rolling it was shown that the activation volume, V', had little correlation to the local chemistry, and in all cases was constant or slightly negative with alloying. After recovery there is small increase in V’ in purer regions, which increases substantially with recrystallization. The exception is Mn (Fig. 2), which shows a rapid increase in V’ with increasing Mn content. The V’ measurement here is really a measure of the deformation structure, which decreases substantially with annealing where Mn is high.

Remaining Work
The local mechanical and chemical measurements from the current work are being combined with the texture and x-ray line broadening data of Bag (2011, M.Sc. thesis) to develop a new model for the recovery kinetics of the Fusion product. The data suggest that the dislocation density, which will be deconvoluted from the line broadening, is a better parameter to describe the recovery than stress (hardness), unlike the earlier model of Verdier et al. (Scripta Mat. 37, 1997, 449) for Al-Mg alloys. Finally, ALAMEL simulations of twin orientations observed to be stable at the inter-alloy region after rolling are being done to investigate this curiosity.
Development of High Dielectric Constant Ceramic Films Using Multilayer Electrophoretic Deposition of BaTiO$_3$
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Introduction
Barium Titanate (BaTiO$_3$) is a common ferroelectric material used in energy storage devices known as capacitors. Due to its perovskite structure and high dielectric constant it is widely used in the electronics industry. Electrophoretic deposition is a cost-effective technique to prepare homogenous BaTiO$_3$ green films on various substrates [1]. This colloidal forming technique has processing parameters that are difficult to control therefore void formation and cracking are a common occurrence. These anomalies significantly degrade the material’s electrical properties. The coating normally experiences 10-15% linear shrinkage during sintering which also contributes to the presence of defects. Currently there are several methods that can reduce this problem such as liquid phase sintering using glass enamel, matching the thermal expansion coefficient of the substrate with the film and by using a reaction-bonding technique [2]. These methods are difficult to reproduce and do not tackle the problem of void formation very well. In this study a novel multilayer electrophoretic deposition technique is introduced.

Methods and Results
The particle size distribution of advanced Barium Titanate powder was determined using an LA-910 Horiba Laser Scattering Particle Size Analyzer. The mean particle size was found to be 0.903µm. A Rigaku X-ray diffractometer was used to confirm the composition of the powder and it’s lack of contaminants. 0.225g of powder was ultrasonically mixed in a 30ml Ethanol/Acetone suspension medium with a 2:1 ratio. Two substrates were cut out from Ni foil (125µm), etched, and cathodic electrophoretic deposition was performed on them. One sample was deposited on continuously while the other underwent three deposition/sintering steps. A constant potential of 10V was applied throughout this process. The sintering steps involved drying the samples at 140°C for 30min then heating to 1250°C at a rate of 5°C/min and holding for 1hr in reducing atmosphere. The absence of NiO was confirmed using X-ray diffraction. Further peak broadening analysis comparing the multilayer film to the single layer film of the same thickness showed the existence of larger grains in the multilayer film due to repeated sintering. SEM images (Figure 1) were used to determine the average grain size near the Ni/BaTiO$_3$ interface. A value of 20µm and 1.5µm was found for the multilayer and single layer films respectively. Dielectric measurements were carried out on a Solartron 1260 Impedance Analyzer. The results showed a significantly lower dielectric constant for the multilayer film that was due to the presence of larger grains along the interface. The dielectric losses for the single layer film were higher due to the presence of defects (Figure 2). It is clear that multilayer electrophoretic deposition is an affective way of preventing cracking and covering voids. However, this technique results in lower dielectric constants.

![Figure 1: SEM images of BaTiO$_3$ grains for 1 layer film (top) and 3 layer film (bottom)](image1)

![Figure 2: Dielectric constant (top) and Dissipation Factor (bottom) vs. Frequency for 1 layer film and 3 layer film](image2)

References
Study of the Effect of Strain Rate on Deformation Mechanisms of a Two-Phase Zirconium Alloy Using Synchotron X-Ray Diffraction
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Background
Zirconium and its alloys are used widely in the nuclear industry. The primary phase in all industrially applied zirconium alloys has a hexagonal-close packed crystal structure, resulting in anisotropic behaviour which is further amplified by the strong textures developed during manufacture. Many in-service properties, such as creep and irradiation growth, are strongly dependent on this texture[1]. The evolution of texture during various forming processes is a result of the activation of various deformation modes, slip and twinning, which in turn depend on process variables, like temperature and rate of deformation. In situ diffraction studies measure lattice strains of individual grain families to monitor micro-mechanical deformation behaviour. Previous diffraction studies have investigated primarily the impact of temperature[2] or microstructure[3], but have been performed using interrupted (or quasi-static) testing, which is not reflective of true forming processes. Previous studies of strain rate have been macroscopic in nature, and performed over a relatively small range of strain rates[4]. Thus, real time in-situ studies spanning a wide range of strain rates will enhance understanding of deformation behaviour and texture development in this alloy system.

Methods and Results
In-situ compression tests were performed using synchotron radiation at the Advanced Photon Source (APS) at Argonne National Labs. Brick-shaped samples were prepared from extruded Zr-2.5wt%Nb rod. An alpha + beta anneal was performed on the samples, as previous studies have shown that this heat treatment encourages the activation of twinning during compression. Two sample orientations were prepared, with the loading direction either parallel or perpendicular to a high density of c-axes. Samples were also prepared from rod with different alloying content, to investigate the changing role of interstitial species at different strain rates. Tests were performed at strain rates ranging from 8.5x10^{-4}/s to 5 x 10^{-6}/s (spanning 4 orders of magnitude) to total plastic strains exceeding 10%. Diffraction patterns were measured at rates up to 3Hz. Tests were performed at ambient temperature (~18°C) and 300°C. Preliminary results (Figure 1) indicate clear changes in the post-yield behaviour dependent on rate of deformation.

![Figure 1](image)

Figure 1: Lattice strain evolution in Zr-2.5%Nb compressed at a) 3.1 x 10^{-4}/s and b) 4.8x10^{-6}/s. Post-yield behaviour is different, with the (10-10) grains softening at the low rate and hardening at the higher rate. The (10-11) grains are perfectly plastic post-yield at the higher strain rate. The (0002) grain family appears in the compression direction as a result of twinning at yield, and quickly accommodates large lattice strains.

References
Predicting Corrosion Initiation Sites in Copper Using Finite Element Modeling

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Introduction and Motivation

From a materials science aspect, the nuclear reactor presents a challenging environment for the design of long life components. A large problem is corrosion as it occurs in the coolant and fueling systems. The mechanism behind corrosion initiation at specific sites is still not clearly understood, reducing one’s ability to predict future failure locations. Within Canada, major corrosive effects have been observed in the primary heat transport (PHT) coolant channels of the Point Lepreau CANDU reactor [1]. The prediction of corrosion initiation sites has the potential to reduce operating costs as periodic maintenance checks could be scheduled according to the results of a corrosion model. Corrosion resistant microstructures could also be developed in accordance with the findings of a corrosion model. In corrosion science, corrosion resistance may be described using four attributes including electrochemical, physical chemical, thermodynamic and metallurgical. The metallurgical characteristics of brass and copper samples are of interest to this corrosion study (residual stress and strain and surface topography).

Methodology and Experimentation

In collaboration with a group at another university, EBSD generated grain maps will be imported into a finite element model in order to develop a residual stress/strain map. Corrosion testing of the sample will yield a corrosion map, which will then be compared to the model generated stress/strain distribution. The current hypothesis is that areas of high residual stress and/or high plastic strain correlate to zones of corrosion initiation. Pure copper samples will be analyzed due to the absence of additional phases which may result in thermodynamically favourable zones for corrosion initiation, convoluting potential results.

EBSD data of brass samples used for corrosion testing is currently being analyzed using a finite element model in conjunction with a crystal plasticity code. Material specific parameters used in the code are being optimized to yield the most accurate results. A Voce hardening model has been selected as it was deemed most appropriate for brass and other similar FCC metals (including copper) [2].

Future Work

Development of the finite element model will continue including the addition of material parameters and relationships specific to FCC metals. Additional EBSD data sets will be analyzed in order to support the proposed corrosion theory. The method will be extended to pure copper samples with EBSD and corrosion testing being performed. Surface topography measurements will also be undertaken in order to examine the effect of localized plastic strain on certain slip systems, their relation to topographical changes and the potential influence on corrosion.

References


Temperature dependence of the uniaxial deformation behavior of Zircaloy-2 alloy

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Introduction:

It is well known that temperature has a great influence on the relative (Critical Resolved Shear Stress) CRSS values of potentially active deformation modes of metallic alloys. With an increase of temperature, dislocation glide becomes easier. Temperature dependence of different deformation modes in Zircaloy-2 alloy has been studied under uniaxial deformation, which gives better understanding of the deformation behavior of zirconium and its alloys at elevated temperatures.

Results:

In situ neutron diffraction lattice strain measurements during compressive loading tests have been done on Zircaloy-2 alloy at different temperatures. The experimental results show change of the deformation behavior with increasing temperature. Among the operating deformation modes, basal slip is found to have equivalent contribution as prism slip at elevated temperatures. Twinning is found to still be present at 300°C but has been eliminated at a temperature of 500°C.

Fig. 1 Macro true stresses at which different slip systems along stress direction start to operate along RD and ND direction (Room temperature data is from [1]).

References:


The Effect of Microstructure on the Mechanical Behaviour of Dual-Phase Steels

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Introduction
There is a continuing trend in the automotive industry to move towards lighter, more fuel-efficient vehicles. To ensure competitiveness of ferrous alloys, new grades of Advanced High Strength Steels (AHSS) are being developed with a combination of superior strength and good formability. Dual-Phase (DP) steel is the most commonly used AHSS and it comprises martensite particles distributed in a ferrite matrix. This grade of steel is characterized by its distinct mechanical behaviour of continuous yielding at low stresses, very high initial work hardening rate and large uniform elongation. These phenomena are attributed to the inhomogeneous plastic flow arising from the strain incompatibility between the hard, non-deforming martensite and the soft, ductile ferrite. Furthermore, the mechanical behaviour of DP steel is highly dependent upon the size, spatial distribution and volume fraction of martensite particles as well as the ferrite grain size. The present research seeks to investigate these effects by designing various dual-phase microstructures through heat treatments prior to the inter-critical annealing step.

Methods and Results
A DP780 steel sheet (supplied by US Steel Canada) was subjected to a series of pre-treatments followed by inter-critical (IC) annealing in the dual-phase region. Two sets of pre-treatments were employed: Quenching and Tempering (QT) and Austempering (AT). For the QT treatment, 100mm x 20mm samples were heated to the single phase austenitic region at various temperatures for 30 minutes, quenched to 0°C (i.e. in ice and water mixture), tempered for one hour at 600°C (QT6) and finally quenched to 0°C. For the austempering pre-treatment, the samples were heated to the austenitic region at 920°C for 30 minutes, air-cooled to 500°C, held for 20 minutes and finally quenched to 0°C (AT5). The pre-treated specimens, along with the samples of the as-received cold-rolled material (CR), were then given an inter-critical (IC) annealing treatment of 2 minutes at various temperatures followed by quenching to 0°C. Total of 22 different microstructures were produced and then examined via SEM and TEM. Figures 1 to 3 show three examples of such microstructures. In addition to the martensite and ferrite, carbide particles were also detected in virtually all microstructures regardless of the IC annealing temperature. Only long IC annealing treatments (30 minutes) produced complete carbide dissolution. Finally, it was found that the kinetics of the transformation during IC annealing depends upon the starting microstructure as follows: QT+IC < CR+IC < AT+IC.

In the next step, uniaxial tensile tests were performed and the work hardening exponent, \( n = \frac{d\sigma}{d\varepsilon} \), as well as the instantaneous hardening exponent, \( n_{\text{inst}} = \frac{d\log\sigma}{d\log\varepsilon} \), were calculated. It was found that the microstructure has a significant effect on the tensile behaviour of DP steels. The work hardening exponent has a direct correlation with the martensite volume fraction, \( f \), while it has an inverse relationship with the martensite particle size, \( r \). This can be observed in Figure 4 where the work hardening exponent (at 2% true strain) is plotted against \( f/r \). Additionally, the size and spatial distribution of martensite also affects the tensile behaviour. Figure 5 shows the engineering stress-strain plots for selected microstructures with similar volume fractions of martensite (~14.2%). Figure 6 presents the evolution of \( n_{\text{inst}} \) with engineering strain for the microstructures of Figure 5. It can be seen that the CR+IC microstructure, with the most uniform size distribution of martensite particles, produces the most desirable tensile behaviour in terms of high strength, large uniform elongation and high work hardening exponent while the QT+IC (with the least uniform size and spatial distribution of martensite particles) has the most inferior tensile properties.
Effects of microstructure on tensile behaviour in aluminum-containing TRIP steel

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Introduction
Transformation-induced plasticity (TRIP) steels undergo a phenomenon where the metastable retained austenite phase transforms into martensite during deformation. This “TRIP effect” results in high strength, high elongation and good crashworthiness that make the material ideal for automotive structural applications. Traditionally, the main alloying element in these steels is silicon, but new compositions have been introduced where the silicon is replaced with aluminum to improve the steel’s galvanizing properties. The current work studies two distinct microstructures in aluminum TRIP steel (labelled as equiaxed and lamellar) and how microstructure affects the austenite transformation during uniaxial tensile loading.

Methods and Results
The as-received material is a hot-band aluminum TRIP steel. After cold-rolling to a thickness of 1 mm, different heat treatment schedules were employed to obtain the two microstructures, shown in figure 1. A set of preliminary heat treatments were conducted where the temperatures and times of the heat treatments were varied to produce a TRIP microstructure with the maximum volume fraction of retained austenite, as determined via magnetic measurements. The volume fraction of retained austenite was used to evaluate the heat treatments because of its direct correlation to high ultimate tensile strength and high uniform elongation values. Results from uniaxial tensile tests (figure 2) show that the equiaxed microstructure exhibits higher strength and lower ductility than the lamellar microstructure, which is similar to findings from previous work with a silicon TRIP steel. Magnetic measurements will be conducted on a set of samples that are deformed to various strains to track the TRIP effect throughout the deformation process and to examine the retained austenite stability in each of the microstructures.

Figure 1: Optical micrographs of lamellar (top) and equiaxed (bottom) microstructures. Ferrite is tan, bainite is dark brown, martensite/retained austenite is white

Figure 2: Engineering stress-strain curves for both microstructures
Study on Thermal Creep of Zr-Excel Alloy by Modification of Crystallographic Texture  
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Synopsis
Crystallographic texture plays an important role in HCP materials (Zr-based alloy) which is being used in CANDU pressure tube. The preferential orientation of crystallographic planes towards certain direction makes the current pressure tube anisotropic (during deformation) in service condition. The dual phase high strength Zr-Excel alloy has developed in CRNL (Chalk River Nuclear Lab) for the betterment of creep properties. However, the primary objective of this alloy development was to use for Generation-IV reactor in High Efficiency Channel (HEC) application which requires a significant improvement in strength. Moreover, in later when the conceptual design has established for HEC application a tremendous change in texture has required than the typical texture experiencing in CANDU. This is because, in HEC application the two end points of the pressure tube has more constraint and this allows insignificant elongation. The existing fabrication recipe for pressure tube shows significant elongation due to its preferred orientation of certain important planes. This leads to develop an isotropic texture in order to minimize the anisotropic deformation behaviour. As received pressure tube materials were heat treated at a range of temperature and the content of transformed β-phase has quantified which has randomized the major planes. The current project is focused on modifying the texture of Zr-Excel alloy which is considered as Gen-IV CANDU reactor (for HEC application) pressure tube materials. Moreover, the thermal creep properties of this particular alloy will also be investigated. All these information will provide an effective tool for developing HEC application for Gen-IV reactor.

Introduction
Atomic Energy of Canada (AECL) is the developer of CANDU (CANada Deuterium Uranium) which is one of the three major commercial power reactors in the world. Moreover, owing to the evolutionary nature of these advanced reactors, advanced technology from the development programs is also being applied to operating CANDU plants, for both refurbishments and upgrading of existing systems and components. Each of the CANDU reactors has modified or designed for the advancements in materials, fuel, safety, plant operations, components and systems, environmental technology, waste managements. The current project is part of this development program of Generation-IV CANDU SCWR and has mainly focused on the development and improvement of the primary containment (pressure tube) of the Generation IV reactor as well as for a brief study of thermal creep of the associated materials of the pressure tube.

Method and Results
Rectangular shape samples were cut and heated at a range of temperature (865°C to 950°C) in a controlled environment (to protect from oxidation). Metallography had been conducted to investigate the microstructure and morphological changes in phase and other microstructural features. The main objective of this heat-treatment is to achieve an appropriate condition by exceeding the β-transus temperature which leads an isotropic texture in the associated alloy. Texture measurements by neutron diffraction will be conducted after heat treatment to investigate the degree of randomness in texture and eventually will co-relate with different temperature to show the variation. Thermal creep properties of Zr-Excel alloy micro-pressure tube will investigate under Laser Dimension Sensor to measure the secondary creep rate in variant condition (at different temperature and stress). Finally a self-consistent model will be aimed to construct by co-relating with experimental creep data in order to use for arbitrary stress state.

![Figure](image.png)

Figure. (a) As-received (b) Air cooled from 930°C (c) Water-quenched (WQ) from 930°C and (d) SEM on 930°C WQ sample

Conclusions
Crystallographic texture modification has required for the proposed HEC application in Gen-IV CANDU reactor to use in a higher temperature and pressurized condition. A random texture other than the preferred orientation is prescribed in this occasion for reasonable service period. Moreover, creep properties of Zr-Excel alloy is required to investigate to estimate the deformation in service condition associated with thermal creep.

References
In-situ TEM Study of Irradiation Induced Damage in CANDU Garter Spring Material Inconel® X-750

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Synopsis
Recently, it has been found that CANDU garter spring made of Inconel® X-750 become embrittled after long time reactor exposure. To emulate the neutron irradiation induced phase and microstructural changes and understand the problems, in-situ heavy ions irradiations were performed. In this study, it is unveiled that irradiation induced phase change, lattice defects and cavities all contribute to spacer embrittlement. Dynamic formation of stacking fault tetrahedras (SFTs) by irradiation was first time ever observed. Through heavy ions irradiations combined with pre-implanted helium, we find that helium interstitials are essential for the cavities formation.

Introduction
Inconel® X-750 is a γ’ Ni₃(Al, Ti) precipitation strengthened Ni based superalloy used for fasteners and centering pins in the cores of pressurized water reactors and boiling water reactors, and in CANDU fuel channels as a spacer material. In-reactor neutron irradiation causes damage by cascades and reaction products resulting in formation of loops, cavities, and other defects, which will strongly affect the mechanical properties. There is concern in the industry that the springs may become embrittled after long reactor exposures and no longer function properly. To study the neutron irradiation damage, TEM in-situ heavy ions irradiation is performed. We benefit from in-situ heavy ion irradiation because: 1. no radioactive production, 2. more accurate parameters, 3. high dose rate, 4. dynamical observation, 5. cost effective.

Methods and Results
Samples were cut from a ready-for-service garter spring, ground and twin-jet electropolished for TEM observation. Samples were then irradiated by 1 MeV Kr⁺⁺ ions at 60°C, 200°C, 300°C, 400°C, 500°C, and 600°C respectively up to 5.4 dpa in an intermediate voltage electron microscope (IVEM). Microstructures evolution and phases changes were observed at several dose steps. Post-irradiation EDX-STEM mapping was employed to analyze the phase change of γ’. Two beam bright field (TBBF) dynamical and kinematical conditions, weak beam dark field (WBDF) imaging and g•b analyses were used to characterize defects. In order to emulate the in reactor neutron irradiation, which produces helium interstitials by a (n, α) transmutation reaction, in-situ heavy ion (Kr⁺⁺) irradiations with pre-injected helium were performed under observation of IVEM.

Irradiation Induced Phase Change
While irradiated at 60°C~400°C, γ’ superlattice reflections disappeared at dose <0.06 dpa, indicating the γ’ precipitates were totally dissolved. Post irradiation EDX-STEM mapping indicates γ’ were not dissolved at this level. At higher dose 5.4 dpa, mapping shows a blurred edge of γ’ precipitates, indicating they are probably going to be dissolved at higher dose, in terms of competition between ballistic mixing and thermal ageing. γ’ precipitates were found stable at irradiation temperature >500°C up to 5.4 dpa. A critical temperature was found in between 400°C and 500°C, where irradiation effects and thermal ageing reaches the equilibrium point. Carbides were found stable at all temperature up to 5.4 dpa.

Irradiation Induced Lattice Defects
TBBF and WBDF observations were carried by using g=200 close to zone axis <110>. Defects consist mostly of SFTs, ½<110> perfect loops. ½<111>: Frank loops formed only at temperature >500°C. Fractions of SFTs and loops are neither temperature nor dose dependent. There is no defects size change with dose, except evolution of Frank loops at elevated temperature. Defects sizes increase with temperature due to the mobility increase of interstitials and vacancies. SFTs formed directly from cascade and number density only depends on the ions flux. Measurement of defect density shows a great increase at low dose and saturation after 0.68 dpa due to damage overlapping.

Irradiation Induced Cavities
There are NO VOIDS found from sample irradiated by Kr⁺⁺ even at high temperature 600°C, indicating the transmutation produced helium may be significant in swelling. As a result, the following experiments were performed. 200 appm He⁺ (50 keV) were pre-implanted within TEM, and then followed by 1 MeV Kr⁺⁺ in-situ irradiation to 20 dpa. After helium pre-implantation to 200 appm at RT, there are no visible implantation induced defects and no helium bubbles. After Kr⁺⁺ irradiation, however, cavities comparable to those in ex-service spacers, with sizes smaller than 5 nm, were observed by using TBBF kinematical condition.

Conclusions
The X-750 spacers lose strength and hardness due to disordering of the principal strengthening phase γ’. Disordering and dissolving of γ’ at reactor temperature will enhance swelling because fine γ’ precipitates are supposed to suppress cavities growth. Large amounts of SFTs and loops can harden the material at even low dose (0.7 dpa). Helium interstitials are essential for nucleation and stabilization of irradiation induced cavities. Those cavities play a vital role in GB embrittlement of the material. In this study, irradiation environment of CANDU reactor was successfully emulated by using heavy ion irradiation with pre-implanted helium. Future work needs to be done to optimize the material.
Investigating the Effect of Cooling Rate on the Microstructure and DHC Behavior of Zr-2.5Nb Alloy

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Introduction
Zr-2.5Nb Alloy, known for its low neutron capture cross-section and good mechanical and corrosion properties, is used as the standard material for pressure tube in CANDU heavy water nuclear reactors. In the industry, there is a great interest in increasing the service life of pressure tubes – in particular, to mitigate the effect of delayed hydride cracking (DHC). DHC is known to be sensitive to the microstructure of the material, and the threshold stress intensity factor $K_{1H}$, which characterizes the critical stress and the susceptibility of DHC, appears to be dominated by crystallographic texture [1]. Thus, it is of interest to investigate the effect of different microstructure produced from cooling Zr-2.5Nb alloys from full β phase region at different rates and understand their impact on DHC property of the material.

Methods and Results
Rectangular samples with dimension 25mm x 14mm x 4mm were cut from annealed Zr-2.5Nb block and subjected to different heat treatments; each sample is heated up to the β phase region (980°C), held for 30 minutes and either water quenched, ice brine quenched, oil quenched, air cooled, or oven cooled. Optical microscopy results showed basket-weave morphology for structures obtained through quenching processes, while slower cooling rates produced parallel plate structures – which coincides with the behavior of other zirconium alloys (Zircaloy-2 and Zircaloy-4) observed in literature under similar conditions [2].

After heat treatment, the samples are hydrided to 100 ppm hydrogen content following standard AECL procedure. CT sized specimens are machined out of each hydrided sample and are subjected to DHC upon cooling tests to determine their DHC properties.

Future Work
SEM analysis to indentify the phases present in the heat treated samples
DHC test data analysis, determining $K_{1H}$ and crack velocity ($V_c$)
Analyzing the DHC behavior of welds in Zr-2.5Nb specimen

References

An investigation of twinning in three dimensions

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Introduction
Twinning is an important deformation mechanism in hexagonal close packed metals such as magnesium (Mg) and zirconium (Zr). Traditionally, a critical resolved shear stress (CRSS) approach has been used to predict twinning. However, the CRSS for twin nucleation is different from that for twin growth, and low Schmid factor twins have also been observed [1]. Two physical explanations have been suggested: (i) neighbouring grains must accommodate twin formation, thus the easy slip direction of the neighbouring grain will control which twin variant forms, and (ii) certain orientation relationships at grain boundaries may be more favourable for twin nucleation.

Experimental Methods
Through-thickness tensile samples were cut from rolled Mg-AZ31B in order to induce extension twins by direct tension along the c-axis. In-situ three-dimensional synchrotron X-ray diffraction (Figure 1) was used to determine the mass and volume of each grain, as well as elastic strain and stress inside each grain during straining up to 1.6%. Using Laguerre tessellation from the measured centre of mass and volume of each grain, grains were mapped into a crystal plasticity finite element code. The experiment and the model will be compared in terms of twin inception and propagation, both statistically (Figure 2) as well as on a local grain neighbourhood level.

Texture Analysis of Metallographic Image with Applications in DHC study

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Introduction
Due to hydrogen’s small atomic radius and active chemical nature, it is impossible to either get rid of hydrogen at manufacture or prevent the absorption of hydrogen into a pressure tube in service. When Hydrogen concentration exceeds its TSS in Zirconium alloys, hydride s will form. Hydrides are a brittle phase in zirconium alloys. As a chain is no stronger than its weakest link, the strength of the pressure tube apparently depends on how hydrides are linked, which is called hydride configuration, viz. hydride orientation, length and distribution. What we need to know is the relation between hydride configuration, thermo-mechanical history, and material properties. The first step is an accurate and reliable measurement of hydride configuration. Here I call it the metallographic texture.

Experiment
Two sets of sample images were analyzed. Samples were cut from tubes which were manufactured from Zr-2.5Nb rods with a 50mm diameter and were produced by hot extrusion and cold-drawing. All samples have the same 100 wppm of hydrogen. Set one is the flanged sample from Goldthorpe’s thesis[1], while set two is from Fredette’s thesis[2]. Set one was heat treated at 350 °C, the procedures among samples differ mainly in whether the sample is loaded or not, the hoop stress is 225 MPa. Set two was homogenized at 334 °C for 24 hours, a hoop stress of 100MPa was applied during cooling. (please refer to the original theses for detail.)

Image Analysis
The study of particle orientation is based on a remarkable property of 2D Fourier transform, for details please come to the seminar.

A is the original image, C is all hydrides with background removed, B and D are the angular brightness distribution of the Fourier transformation of A and C.

Reference

Molecular Dynamics Simulation of Displacement Cascades in α-Zr

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Introduction

Irradiation produced defects lead to the degradation of the mechanical properties of nuclear material. Molecular Dynamics (MD) simulation is applied to study the irradiation effects in solids, not only because of the harsh irradiation environment and increasing cost in experiments, also for the matching time scale (tens of ps) and length scale (tens of nm) of displacement cascade. MD simulations reproduce a system of particles, and numerically solve the motion of interacting particles by couples of classical Newton’s equation. In this work, MD is applied to investigate the formation and evolution of the Frenkel pairs (vacancies and Self Interstitial atoms) in irradiated α-zirconium using a many-body inter-atomic potential.

Methods and Results

The most important factor in MD is the potential, current Zirconium potential is an Embedding-Atom many-body potential from M.I. Mendelev and G.J. Ackland Phil. Mag. Lett. 87 349 (2007). Simulations are performed in MDCASK and MOLDY codes, periodic boundary conditions and link cell methods are applied. The energy of the Primary Knock-on Atoms (PKA) ranges from hundreds to thousands eV to produce cascades at different temperatures. Wigner-Seitz method is used to analyze the residual structure after displacement cascades. The effect of temperature and PKA energy on the production of vacancies and self-interstitial atoms are analyzed. Most MD simulation works on the radiation damage do not consider the external strain field. In this work, displacement cascades produced in α-zirconium within macroscopic strain fields (0.1% and 0.5%) also have been investigated by MD simulation. The effects of strain field on the defects production and cascade formation have been studied.

![Figure 1. Displacement cascade by a 10keV PKA at 300K. Dots represent vacancy and SIA. Facing plane is the basal plane, c-axis is perpendicular to the facing plane. Different stages: Collision Phase, Thermal Spike Phase and Final Phase.](image)

![Figure 2. Effect of Energy on SIA and Vacancy clustering](image)

![Figure 3. Effect of Temperature on SIA and Vacancy clustering](image)

![Figure 4. Number of single and clustered SIAs and Vacancies per cascade as a function of strain.](image)

More defects are produced at higher PKA energy as shown in Fig.2, but not as efficiently as NRT formula prediction. Increasing temperature increases the motion of defects before cooling and leads to more SIA-Vacancy recombination (Fig.3). Fig.4 demonstrates the preliminary results of the strain effects on defects production, uniform tensile strain is applied on a direction. The number of Frenkel pairs in the final states decreases with applied strain, probably for the reason that the strain field enhances the defects motion and recombination. Number of single vacancies increase with applied strain, and less clustered SIAs and vacancies are found in the system with strain. Simulations with even higher strain field are necessary, and further explanation and discussion of defects production are needed.

Future Work

Future works includes development of Zirconium-Hydrogen potential. Hydrogen is an embrittlement agent in zirconium alloy and also associated with Delayed Hydride Cracking. It will be worthwhile to investigate the hydrogen diffusion and irradiation effects on hydride by MD simulation. Zirconium-Hydrogen Potential should be developed prior to further MD work.

Reference

Measurement of Stress Relaxation at Notch Tips in Zr-2.5Nb Using Synchrotron X-Ray Diffraction

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Introduction

In CANDU nuclear reactors, pressure tubes are subjected to high temperature as 250°C~310°C and about 10MPa pressure which results in an initial axial stress of about 65MPa in the pressure tube wall and an initial hoop stress of about 125MPa[1]. Flaws on the surface of pressure tubes naturally cause localized stress increases, providing the possibility of crack initiation through DHC (Delayed Hydride Cracking). During operation, stress relaxation occurs around the flaw tip that minimizes the crack happening, and thermal creep is one of the likely reasons[2]. Thus understanding how the stress relaxes at flaw tips is important for evaluating currently operating pressure tubes. In this study, synchrotron X-ray diffraction was implemented to measure the relaxing of stress/strain field near the notch tip of pressure tube material — Zr-2.5Nb.

Methods and Results

C-shaped samples with different notch root radii (15μm or 30μm) were subjected to pre-creep processes with a series of different time periods including 1hour, 3hours, 10hours, 30hours and 90hours. Temperature of 310°C and uniaxial load \(K_{\text{eff}}=6\text{MPa} \sqrt{\text{m}}\) were maintained during the creep process. Then strain measurements of the notch tip area were carried out on these samples with the same load as above at room temperature using synchrotron X-ray diffraction. Matlab programmes were applied to analyze the experimental data. Strains along both transverse direction (TD-loading direction) and radial direction (RD) were obtained. From the strain maps shown in Figure 1 and Figure 2, it is evident that the lattice strain along TD is tensile in front of the notch while in RD compressive strain appears at the same area. The highest tensile strain occurs at about 0.02μm from the notch tip and decreases with creep time indicating that the localized stress was relaxed due to thermal creep. The compressive strains have a similar relaxing trend with the lowest strain value at about 0.04μm from the notch tip. Strains obtained from \{0002\} peak and \{10\10\} peak are plotted separately along the line extending from notch tip into the sample, as shown in Figure 3. The anisotropy of thermal creep can be found: the \{10\10\} strains decrease faster than \{0002\} orientation especially for the transverse direction.

Future work

Finite element modeling is being set up with KKA creep code written in FORTRAN to simulate the thermal creep relaxation and compare with the experiment results. In addition, further experiments will be carried out for irradiated samples to study the effects of irradiation hardening on the stress relaxation of pressure tube material.

References

Use of a Genetic Algorithm for Optimization of a Plasticity Code

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Introduction

The Elasto-Plastic Self Consistent model is a computer program created at Los Alamos National Laboratory (1). It is used primarily to model the deformation of solids undergoing thermo-mechanical loading. In order for this model to function, it requires an input file specifying single-crystal properties of the material to be simulated. The parameters listed in this file include the elastic stiffness tensor, available slip and twinning systems, work hardening parameters, and several others. Choosing these parameters correctly is essential to producing results that match empirical observations. In order to find the best possible parameters, a genetic algorithm written by Charles Mareau was used to compare the model results to experimentally measured macroscopic flow curves, lattice strain curves, and Lankford coefficients (2) collected on samples of Zircaloy-2, an alloy commonly used in the nuclear industry.

Description of Algorithm

The genetic algorithm first reads in several input files telling it where to find the experimental data and model results, as well as the upper and lower bounds on all model parameters being refined. An initial population of 40 complete model parameter sets is generated randomly in order to span as much of the parameter space as possible. These 40 initial parameter sets are then each sent to their own instance of EPSC, causing 40 different sets of model data to be generated and compared to the experimental data. The algorithm then attempts to emulate biological evolution by taking the top performing 20% of the parameter sets and “breeding” them with each other. This breeding consists of taking traits from two parent sets and combining them to create a child that is similar to both parents but at the same time unique. This process can then be repeated for several generations until a satisfactory fit to the experimental data is reached. Figure 1 is a plot illustrating the effectiveness of this method after 90 generations of refinement.

![Figure 1: Fit obtained for compressive and tensile loading (A) and the error calculated by the fitness function after each generation (B).](image)

References


In-Situ Study of Heavy Ion Irradiation In Pure Zirconium
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Introduction
Neutron irradiation alters the mechanical properties of core components of nuclear reactors, which are exposed to service temperatures below 40% of their homologous temperature, making these parts susceptible to hardening, loss of ductility, localised plastic deformation and plastic instability [1-2]. In all these cases, it is important to emphasize the impact of radiation damage on the microstructure of core components for the better safety of nuclear power plants. In typical microstructural investigations by neutron irradiations, samples have been examined in electron microscopes after irradiation to a certain dose level, which provides only the snapshots of final state of damage at that specific dose level [3]. It is not only the final state of the material that is important in predicting the material performance but also the path taken to reach the final state [4]. These studies have left many unanswered questions concerning the mechanisms, kinetics and the driving forces involved in microstructural evolution due to the dynamic behavior of this process. For successful prediction and assessment of material performance over a long duration in irradiation environment, it is crucial to understand the basic formation mechanisms of radiation damage at lower doses and its accumulation at higher dose levels. While neutron irradiation will always be required to qualify materials for reactor application, ion irradiation provides rapid means of elucidating mechanisms and screening materials for the most important variables [4]. In contrast to neutron irradiation, ion irradiation enjoys considerable advantages, such as (1) higher damage rates ~ 10^3 dpa/s compared with nuclear reactors ~10^{-7} dpa/s, (2) little or no residual radioactivity(3) precise control of irradiation conditions (4) a lower irradiation cost than neutron irradiation [4].

In this study, we have reported the direct observations on heavy ion (Kr+2) irradiation induced changes in microstructure of pure Zr at different temperatures using intermediate voltage electron microscope. Experiments were carried out at the unique and enhanced facilities of Argonne National Laboratory Intermediate Voltage Electron Microscope Tandem Facility (IVEM-Tandem), which allowed us to follow dynamically the evolution of damage microstructures in pure Zr over a larger dose and temperature range. We particularly concentrate on generation of small defects directly occurring from cascade collapse at very low dose, and their evolution as the dose increases at different temperatures. Interaction of these defects with existing microstructure and other defect clusters has also been discussed. This in-situ TEM study of defect behaviors in pure Zr at different temperatures furthers our understanding of radiation induced defects by neutron irradiation [3-5].

Experiments and Results
In-situ heavy-ion irradiation experiments on Zr were carried out using IVEM-Tandem at irradiation temperatures 300, 400 and 500°C for the purpose of gaining fundamental understanding of radiation damage in reactor components. Thin foils were irradiated with 1 MeV Kr^{+2} ions to different damage levels ranging from 0.01 dpa to 1 dpa at a dose rate of 10^3 dpa.s^{-1}. Formation of nano defects directly from individual displacement cascades at the early stages of damage development at very low dose (0.01 dpa) has been observed. These defects with a diameter ranging from 2 to 3 nm were measured in area density and mean size. It is found that there is significant dependence of defect formation, number densities, and size distributions on irradiation temperature. Number density of defects decreases with increasing temperature while mean size of defects increases, whereas Power law relationship was found between dose and defect number density. Temperature and dose dependence of defect yield was also investigated. Defect yield decreases significantly with increasing the dose and the temperature. At high doses complex microstructures were developed at all irradiation temperatures, such as formation of large dislocation loops. Ex-situ TEM analysis reveals that at 300°C these loops have <a> and <c> component burgers vectors (b=1/3<11-20>), whereas, at 400°C and 500°C dislocation loops have both <a> and <c> (1/6<20-23>) component burgers vectors. Mechanism of defect formation and development has been discussed.

References
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