members, at least one of which should be from the department, will give a critical review and examine the student on material contained in or related to the proposal.

The Ph.D. Comprehensive Examination will be in two parts. Part I will cover, at the undergraduate level, topics central to materials science and engineering. Credit for this part will be given to a candidate who has successfully completed the comprehensive examination previously required of M.Sc. and M.A.Sc. students. Part II will test the candidate's knowledge at an advanced level. Candidates will be expected to show the greatest depth of knowledge in their field of research but will also be expected to demonstrate knowledge of fields related to their areas of specialization. Part II must be completed within two years of entry into a Ph.D. program at McMaster.

Candidates are expected to begin their thesis research soon after registering for Ph.D. studies. Candidates will be required to submit a thesis which embodies the results of original research and to defend the thesis in the Final Oral Examination.

There are opportunities to take courses from visiting and adjunct professors and for part of the research to be conducted at other universities that collaborate with various faculty in the department.

Courses

Many of the 700-level courses offered by the Department are quarter course modules. These are identified by a pound (#) sign and are offered in 6 week slots. Half courses are identified by an asterisk (*) and last one term (approximately 12 weeks). The course structure is designed so that most courses are available on a two-year basis, subject to student demand and faculty resources. Some courses are offered every year. Students should select a program of study in consultation with their faculty supervisor and be aware of the prerequisite requirements of some courses.

The following courses, which are available to senior undergraduate students, are also offered for graduate credit at the M.Sc. and M.Eng. level only. Graduate students taking these courses are regularly required to do extra course work beyond that required of undergraduates in the 400-level course.

***6C03 / Modern Iron and Steelmaking / K.S. Coley, G.A. Irons**
Theory and practice of ironmaking. Heat and material balances, ironmaking reactors, raw materials, direct reduction and new processes. Thermodynamics and kinetics of steelmaking.Hot metal treatment; static and dynamic process control; deoxidation; casting; specialty steelmaking; inclusion engineering.

***6D03 / Materials and the Environment**
The oxidation of metals and alloys; electrochemical principles and methods applied to aqueous corrosion and its control.

***6E04 / Computational Modeling of Microstructure Formation / Staff**
(cross-listed as Computational Science and Engineering *6E04)
Introduction to explicit and implicit finite difference and finite element simulation techniques for PDE's used in materials science and engineering.Applications to microstructure formation, reaction-diffusion kinetics and interface dynamics.Introduction to parallel methods. Course evaluation will be based on a term project.

***6FF3 / Synthesis, Applications and Environmental Impact of Nanomaterials / G. Botton**
Review of methods of synthesis of nanoscale materials approaches (bottom-up and top down), review of the fundamental properties of nanoscale materials (thermodynamic, mechanical, optical, electronic). Discussion and presentations on many of the applications of these materials in fields of mechanical properties, energy storage, electronic and magnetic, optical, etc.

***6G03 / Characterization of Nanomaterials**
Interaction of electrons and photons with matter. Imaging methods with electron microscopy, scanning probe techniques, x-ray photoelectron spectroscopy and x-ray absorption analysis with high spatial resolution.

***6H03 / Thin Film Science and Engineering / I. Zhitomirsky**
Deposition and fabrication techniques, surfaces, growth mechanisms, epitaxy, defects, kinetic effects in thin films, materials science aspects, applications and properties of thin films.

***6I03 / Sustainable Manufacturing Processes / G.A. Irons (cross-listed as SEP *6I03)**
Sustainable development, materials cycles, methods for measuring environmental impact, life cycle analysis, waste treatment and recycling technologies.

***6NN3 / Computational Modelling in Materials Engineering / Staff**
Numerical methods are introduced and used to model selected problems in materials science involving mass transfer, molecular dynamics and electronic properties.

***6P03 / Properties of Polymeric Materials / G. Xu**
Structure of amorphous and crystalline polymeric materials; mechanical, electrical and optical properties and their modification through processing.

***6R03 / Ceramic Science / Staff**
Microstructural development and properties of traditional ceramics.Acidic, basic, neutral and nonoxidizing refractories; ferro-electric, piezo-electric and ferromagnetic ceramics; super-ionic and structural ceramics.

***6T03 / Properties and Processing of Composites**
This course is intended to provide students with the knowledge related to the structure and properties of a range of composite materials systems. Topics include micromechanics of

composites, intrinsic properties of matrix materials and reinforcements; elements of the mechanics and thermodynamics of interfaces; fabrication of composites materials, modelling of physical properties of composites with the emphasis on mechanical properties, thermal properties and electrical conductivities using Eshelby method. Recent developments in composite materials systems will also be covered.

ENG *6T04 / Materials Selection in Design and Manufacturing / J. McDermid
Materials selection charts, materials selection with mechanical constraints, coupled materials selection and processing/fabrication routes, effect of microscopic and macroscopic shape of materials selection, design of hybrid materials, eco-selection.

The following courses are offered for graduate credit only:

***701 / Graduate Seminar (Master's)**
Each student is required to prepare and present a major seminar, based upon extensive research work and literature surveys, on any topic of current research interest in Materials Science and Engineering. A grade will be assessed based on overall performance in the course.

***702 / Graduate Seminar (Ph.D.)**
Each student is required to prepare and present major seminars, based upon extensive research work and literature surveys, in areas related to their current research. A grade will be assessed based on overall performance in the course.

Thermodynamics and Kinetics

***711 / Advanced Thermodynamics / Staff**
Solution thermodynamics including gas, liquid and solid equilibria. A background in basic thermodynamics of solid state systems is required.

***712 / Phase Transformations / J.J. Hoyt**
Diffusion in binary and ternary systems. Selected topics in phase transformations including: nucleation and growth phenomena; diffusionless transformations; morphological development, control and instability; influence of defects on transformations.

***713 / Computational Thermodynamics / D.V. Malakhov**
Scientific heritage of J.W. Gibbs.Lattice stabilities.Reference states. Thermodynamic models of phases including sublattice model, quasi-chemical model, associated solutions, partially ionic liquids, etc. and their application to metallic systems, oxides, salts and aqueous solutions. Usage of structural information for choosing a proper phase model.Calculation of equilibrium in gaseous systems.Magnetic contribution to the Gibbs energy.Order-disorder transformations and their modeling. Thermodynamic principles hidden behind phase diagrams.Driving forces for the onset of precipitation. Isonucleation diagrams. Thermo-Calc and TQ interface. Simultaneous treatment of heterogeneous experimental information (CALPHAD method).Fortran 90/95 programming.

#714 / Phase Field Methods in Microstructure Modeling /N. Provatas
The course examines microstructure formation in pure materials and alloys. We begin with an examination of sharp interface kinetics used to describe Diffusion controlled free-boundary evolution in phase transformations. We will then use statistical thermodynamics to motivate the development of basic phase field models relevant to solidification and solid-state microstructure evolution. Finally, we study numerical algorithms for simulating basic phase field equations.

Defects in Solids

***720 / Point Defects and Materials Behaviour / Staff**
An analysis of the point defects equilibria including vacancies, interstitials and substitutional atoms. Experimental techniques for their determination, Krüger-Vink diagrams, ionic conductivity/defect concentration relations.Their role in the deformation of metals, radiation damage, embrittlement, cold-working and hardening; concepts and practice.

Materials Characterization

#730/ XRD2 and XRD# Diffraction Methods for Materials/ J. Britten
This course is a study of 2D and 3D X-ray diffraction for the characterization of crystalline solid materials. We will examine the diffraction information obtained in phase, texture and residual stress analyses of metals, coatings, thin films, polymers, etc. using area detector techniques. We will look at safety, sample preparation, data processing software and interpretation of results. The students will study their own research samples and present their analyses to the class.

#731 / Introduction to Electron Microscopy / G. Botton
(cross-listed as Biomedical Engineering #731)
Electron sources, optics, development of scanning, transmission and scanning-transmission electron microscopes. Electron-solid interactions, production of secondary electrons, x-rays. Quantitative microanalysis in the scanning electron microscope.

#732 / Analytical Electron Microscopy / G. Botton
(cross-listed as Biomedical Engineering #732)
Comparison of analytical techniques, low voltage and environmental SEM. Convergent beam diffraction methods, microanalysis in the TEM with EDS and EELS. High resolution TEM, high angle dark-field methods, EELS near-edge structure analysis.

#733 / Materials Characterization by Electron Microscopy / G. De Silveira
Materials Characterization by Electron Microscopy is intended as an introduction to the theory, physical and operating principles of scanning electron microscopy, focused ion beam microscopy and spectroscopy techniques. It provides students with competence in the characterization of a wide variety of conductive and non-conductive nano-scale materials,

which is further developed with hands-on assistance during the graduate research project.

Surfaces and Interfaces

#740 / Interfacial Phenomenon in Materials Science / J. McDermid
Introduction to interfaces including free surfaces, grain boundaries and coherent and incoherent precipitate interfaces.Introduction to surface analysis techniques such as scanning Auger microscopy, X-ray photoelectron spectroscopy and secondary ion mass spectroscopy. Interfacial chemistry including adsorption isotherms, wetting of solid interfaces by liquids and solid/vapour interfaces. Interfacial phenomenon including segregation, formation of secondary phases and interfacial reaction phases, role of interfaces in creep, corrosion phenomenon, interfacial cohesion and the role of crystallographic anisotropy. Course evaluation will be based on assignments and a term project.

***743 / Advanced Topics in corrosion Science and Engineering / J.R. Kish**
A fundamental discussion on the structure of electrified interfaces, dynamic electrochemistry, mixed potential theory, mass transport,passivity, and corrosion measurement techniques. A selection of problems (with worked solutions) and research topics will be provided to clarify the electrochemical theories of corrosion and methods for corrosion control and protection.

#745/ Electrochemical Techniques: Theories & Applications/ J.R. Kish
This course is concerned primarily with a fundamental discussion of the major electrochemical techniques to familiarize the students with the associated set of relative strengths and limitations. Specific topics addressed include structure of the electrified interface, Butler-Volmer equation for electrode dynamics, reference electrodes, hydrodynamic electrodes, linear sweep & cyclic voltammetry, potentiodynamic polarization and electrochemical impedance spectroscopy. A selection of student-led lectures on applications is provided to clarify the strengths and limitations of these measurements in the field of electrochemical science and engineering, with particular emphasis on corrosion science and engineering.

#780 / Metallic and Non-metallic Coatings / J. McDermid
Electrochemical basis of metallic coating protection systems, governing phase equilibria in metallic coating systems, gas/metal reactions, reactive wetting at interfaces, microstructural development of metallic coating systems on ferrous substrates, non-metallic and composite coatings, engineering properties and practical applications of coating systems.

Mechanical Behaviour of Solids

#751 / Effect of Length Scale on Mechanical Behaviour/ D.S. Wilkinson, M. Niewczas
Effect of microstructure — from the nano- to the macroscopic level — on the strength, ductility and toughness of materials, in both single phase and multiphase materials; modelling approaches, including continuum approaches, dislocation mechanics and atomistic modelling.

#753 / Fracture Mechanisms in Solids / D.S. Wilkinson, J.D. Embury

Mechanisms leading to fracture in solid materials. Ductile fracture by the nucleation, growth, and coalescence of voids; damage accumulation concepts; brittle fracture in metals and ceramics; crack propagation; crazing in the polymers.

#754 / Fracture Mechanics / J.D. Embury, D.S. Wilkinson
Elastic and plastic behaviour of bodies containing defects including: linear elastic fracture mechanics; description of crack tip plasticity; use of LEFM in design; ductile-brittle transition; crack propagation under conditions of creep or fatigue. Offered from time to time, depending on interest and demand.

#755 / Deformation of Crystalline Solids / J.D. Embury, D.S. Wilkinson, M. Niewczas
A quantitative treatment of the mechanical behaviour of crystalline materials, with emphasis on elasticity and plasticity. Topics include: ideal strength, isotropic and anisotropic elasticity, dislocations, continuum models, work hardening, strengthening mechanisms, time dependents effects. This course is offered in alternate years.

Physical Properties of Solids

***760 / Electronic Materials / I. Zhitomirsky**
Basic magnetic properties of materials, magnetic structure, domains, critical behavior at the ordering temperature, soft and hard magnetic materials. Ferroelectric, piezoelectric, pyroelectric and optical properties of materials.Capacitor materials.Semiconductors.Materials for energy storage and generation. Materials selection and design. Nanocomposites.

***764 / Solid State Polymer Analysis / G. Xu**
Analytical solid state methods are employed to determine the influence of polymer structure on physical and chemical properties.

#765 / Selected Topics in Polymer Science & Engineering/ S. Zhu, G. Xu
Discussions on topics of current interest in polymer science and engineering, such as structural characterization, diffusion in bulk solution, network formation, colloid stabilization, and flocculation. (Note: This course may also be taken for half course credit as Chemical Engineering *770. Such students will be required to complete the mid-term exam and a project as well. Students taking this course for quarter course credit as Materials Science #765 will be required to complete the mid-term exam.)

Materials Processing

#771 / Principles of Heterogeneous Kinetics / K.S. Coley
Basic principles of chemical kinetics; transport processes by interfacial chemical reactions; empirical rate expressions based on experimental data, and theoretical rate equations based on proposed mechanisms; rate limiting steps and process control.

#773 / Properties of Metallurgical Slags / K.S. Coley
This course will present a theoretical picture of slags and their properties and will demonstrate how these properties can be controlled to help optimise metallurgical processes. The following aspects of slag properties will be covered: Slag structure and its relationship with basicity; Basicity concepts from V-ratio to optical basicity; the relationship between structural chemistry and physical property of slags; Basicity and slag capacities. Industrial examples will be taken from Oxygen steelmaking, ladle metallurgy and continuous casting.

***774 / Injection Metallurgy / G.A. Irons**
The transport phenomena associated with the injection of gas or gas and particles into liquid metals are examined. Specific topics include: pneumatic conveying, particle injection, flow regimes, mixing, plume modelling and refining reactions.

***775 / Physical and Mathematical Modelling in Materials Processing / G.A. Irons**
Criteria for similarity; analysis of tracer mixing; mathematical models of combined fluid flow, heat transfer and mass transfer. Critical review of case studies in the literature.

Special Topics

#791 / Special Topics in Materials Science and Engineering/ Staff
From time to time, modules will be offered on subjects of interest to the Department faculty.

***792 / Special Topics in Materials Science and Engineering/ Staff**
From time to time, courses will be offered on subjects of interest to the Department faculty.

In addition to these courses, there are many courses offered by other departments, which may be considered. The selection of such courses should be done in consultation with the student's supervisor and will be authorized by the Chair of the Department. Students should consider courses offered by the Departments of Engineering Physics, Chemistry, Chemical Engineering, Mechanical Engineering, Physics and Astronomy, and Mathematics and Statistics.

Research in Materials Science and Engineering

The Department of Materials Science and Engineering provides opportunities for research in a broad range of fundamental and applied topics including materials processing and recycling, nano-technology and nanoscale materials science, electronic materials and structural materials. Detailed descriptions of research activities can be found in the web pages for each faculty member and are briefly listed below: microstructure and interfaces in nanoscale functional materials, electronic structure and spectroscopy of complex oxides and alloys, electron microscopy and electron energy loss spectroscopy techniques (G. Botton); kinetics and thermodynamics of high-temperature reactions in materials processing and service, physical chemistry of iron and steel making (K. Coley); modelling and experimental techniques to help the steel industry optimize their production (N. Dogan); biomaterials development and characterization with a focus on the dependence of bone growth on surface properties for