# Metallurgical and Materials Engineering

## Degrees Offered

- Master of Engineering (Metallurgical and Materials Engineering)
- Master of Science (Metallurgical and Materials Engineering)
- Doctor of Philosophy (Metallurgical and Materials Engineering)

## Program Description

The program of study for the Master or Doctor of Philosophy degrees in Metallurgical and Materials Engineering is selected by the student in consultation with her or his advisor, and with the approval of the Thesis Committee. The program can be tailored within the framework of the regulations of the Graduate School to match the student's interests while maintaining the main theme of materials engineering and processing. There are three areas of specialization within the Department:

- Physical and Mechanical Metallurgy;
- Physicochemical Processing of Materials; and,
- Ceramic Engineering.

The Department is home to five research centers:

- Advanced Steel Processing and Products Research Center (ASPPRC);
- Center for Advanced Non Ferrous Structural Alloys (CANFSA)
- Center for Welding Joining, and Coatings Research (CWJCR);
- Colorado Center for Advanced Ceramics (CCAC); and,
- Kroll Institute for Extractive Metallurgy (KIEM).

The Nuclear Science and Engineering Center (NuSEC) also operates closely with the Department.

A Graduate Certificate is offered by each Department Center – the requirements for the Graduate Certificate are:

1. Be admitted to MME Graduate Certificate Program upon the recommendation of the MME Department.
2. Complete a total of 12 hours of course credits of which only 3 credit hours can be at the 400 level.

The specific courses to be taken are determined by the Graduate Advisor in the Department Center selected by the candidate. A cumulative grade point average of B or better must be maintained while completing these requirements.

## Degree Program Requirements

The program requirements for the three graduate degrees offered by the Department are listed below:

## Master of Engineering Degree

Requirements: A **minimum total of 30.0 credits** consisting of:

| Coursework | Credits | |
|---|---|---|
| Approved Coursework* | 18.0 - 26.0 | |
| MTGN501 | MME GRADUATE SEMINAR ** | 1.0 |
| MTGN700 | GRADUATE RESEARCH CREDIT: MASTER OF ENGINEERING (or designated design course) *** | 3.0-5.0 |

* 18 of the 26 credits must be taken from the Metallurgy or Materials Science courses. All other course credits can be taken in any department.

** Students are expected to enroll in this seminar every semester, but a maximum of 1 credit may apply toward the degree.

*** Students can choose to fulfill the NT masters degree requirements by either taking 30 credits, including 3 hours of a "design" course, or take 25 hours of course credits and have 5 hours devoted to a project; in that case, students will have to defend an engineering report to a 3 person committee.

**Designated Design courses include:**

| | | |
|---|---|---|
| MTGN414 | ADVANCED PROCESSING AND SINTERING OF CERAMICS | 3.0 |
| MTGN445 | MECHANICAL PROPERTIES OF MATERIALS | 3.0 |
| MTGN461 | TRANSPORT PHENOMENA AND REACTOR DESIGN FOR METALLURGICAL AND MATERIALS ENGINEERS | 3.0 |
| MTGN464 | FORGING AND FORMING | 2.0 |
| MTGN475 | METALLURGY OF WELDING | 2.0 |
| MTGN549 | CURRENT DEVELOPMENTS IN FERROUS ALLOYS | 3.0 |
| MTGN564 | ADVANCED FORGING AND FORMING | 3.0 |
| MTGN560 | ANALYSIS OF METALLURGICAL FAILURES | 3.0 |

Alternative courses can be substituted with approval from the advisor and department head

**Restrictions:**

1. Only three (3) credits of independent coursework, e.g. MTGN599, may be applied toward the degree.
2. A maximum of nine (9) credits of approved 400-level coursework may be applied toward the degree.
3. Courses taken to remove deficiencies may not be applied toward the degree.

The Master of Engineering Degree can also be obtained as part of the combined undergraduate/graduate degree program.

## Master of Science Degree

Requirements: A **minimum total of 30.0 credits** consisting of:

| Coursework | Credits | |
|---|---|---|
| Approved Coursework* | 18.0 - 23.0 | |
| MTGN501 | MME GRADUATE SEMINAR ** | 1.0 |
| MTGN707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT *** | 6.0-11.0 |

* Minimum of 18 credits of approved coursework is required. 12 credits must be taken from the Metallurgy or Materials Science courses. All other course credits can be taken in any department.

** Students are expected to enroll in this seminar every semester, but a maximum of 1 credit may apply toward the degree.

*** 6.0 to 11.0 research credits, to include MTGN707.

**Restrictions:**

1. Only three (3) credits of independent coursework, e.g. MTGN599, may be applied toward the degree.
2. A maximum of nine (9) credits of approved 400-level coursework may be applied toward the degree.
3. Courses taken to remove deficiencies may not be applied toward the degree.

**Additional Degree Requirements:**

1. Approval of all courses by the Thesis Committee and the Department Head. (Thesis Committee: consisting of 3 or more members, including the advisor and at least 1 additional member from the Metallurgical and Materials Engineering Department.)
2. Submittal and successful oral defense of a thesis before a Thesis Committee. The thesis must present the results of original scientific research or development.

The Master of Science Degree can also be obtained as part of the combined undergraduate/graduate degree program.

## Doctor of Philosophy Degree

Requirements: A **minimum total of 72.0 credits** consisting of:

| Coursework | Credits | |
|---|---|---|
| Approved Coursework* | 36.0 - 48.0 | |
| MTGN501 | MME GRADUATE SEMINAR ** | 1.0 |
| MTGN707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT *** | 24.0-36.0 |

* A minimum of 36.0 credits of approved coursework, 24 of which must be in MTGN or MLGN. Credits previously earned for a Master's degree may be applied, subject to approval, toward the Doctoral degree provided that the Master's degree was in Metallurgical and Materials Engineering or a similar field. At least 21.0 credits of approved course work must be taken at the Colorado School of Mines.
All courses and any applicable Master's degree credits must be approved by the Thesis Committee and the Department Head (Thesis Committee consisting of: 4 or more members, including the advisor, at least 2 additional members from the Metallurgical and Materials Engineering Department, and at least 1 member from outside the Department.)

** Students are expected to enroll in this seminar every semester, but a maximum of 1 credit hour may apply toward the degree.

*** A minimum of 24.0 research credit hours, to include MTGN707.

**Restrictions:**

1. Only six (6) credits of independent coursework, e.g. MTGN599, may be applied toward the degree.
2. A maximum of nine (9) credits of approved 400-level coursework may be applied toward the degree.
3. Courses taken to remove deficiencies may not be applied toward the degree.

**Additional Degree Requirements:**

1. Presentation of a Proposal on the Thesis-Research Project to the Thesis Committee.
2. A passing grade on the written and oral Qualifying-Process (Q.P.) Examinations.
3. Presentation of a Progress Report on their Research Project to the Thesis Committee is strongly recommended; this presentation is usually 6 months after successfully completing the Q.P. Examinations and no fewer than 6 weeks before the Defense of Thesis.
4. Submittal and successful oral defense of a thesis before the Thesis Committee. The thesis must present the results of original scientific research or development.

## Prerequisites

The entering graduate student in the Department of Metallurgical and Materials Engineering must have completed an undergraduate program equivalent to that required for the BS degree in: Metallurgical and Materials Engineering, Materials Science or a related field. This undergraduate program should have included a background in science fundamentals and engineering principles. A student, who possesses this background but has not taken specific undergraduate courses in Metallurgical and Materials Engineering, will be allowed to rectify these course deficiencies at the beginning of their program of study.

## Mines' Combined Undergraduate / Graduate Degree Program for Non-Thesis MS

Students with continuous registration at Mines from the undergraduate to the graduate degree may fulfill part of the degree requirements by double counting six credits, which were also used in fulfilling the requirements of their undergraduate degree at Mines. These courses must have been passed with a “B” or better and meet all other University and Department requirements for graduate credit, but their grades are not included in calculating the graduate GPA.

## Fields of Research

## Ceramic Research

- Ceramic processing
- Ceramic-metal composites
- Functional materials
- Ion implantation
- Modeling of ceramic processing
- Solid oxide fuel cell materials and membranes
- Transparent conducting oxides

## Coatings Research

- Chemical vapor deposition
- Coating materials, films and applications
- Epitaxial growth
- Interfacial science
- Physical vapor deposition
- Surface mechanics
- Surface physics
- Tribology of thin films and coatings

## Extractive and Mineral Processing Research

- Chemical and physical processing of materials
- Electrometallurgy
- Hydrometallurgy
- Mineral processing

- Pyrometallurgy
- Recycling and recovery of materials
- Thermal plasma processing

## Nonferrous Research

- Aluminum alloys
- High entropy alloys
- Magnesium alloys
- Nonferrous structural alloys
- Shape memory alloys
- Superalloys
- Titanium alloys

## Polymers and Biomaterials Research

- Advanced polymer membranes and thin films
- Biopolymers
- Bio-mimetic and bio-inspired materials engineering
- Calcium phosphate-based ceramics
- Drug delivery
- Failure of medical devices
- Interfaces between materials and tissue
- Living/controlled polymerization
- Organic-inorganic hybrid materials
- Porous structured materials
- Self- and directed-assembly
- Structural medical alloys
- Tissue as a composite material

## Steel Research

- Advanced high strength steels
- Advanced steel coatings
- Carburized steels
- Deformation behavior of steels
- Fatigue behavior of steels
- Microalloyed steels
- Nickel-based steels
- Quench and partitioned steels
- Plate steels
- Sheet steels

## Welding and Joining Research

- Brazing of ultra wide gaps
- Explosive processing of materials
- Laser welding and processing
- Levitation for kinetics and surface tension evaluation
- Materials joining processes
- Pyrochemical kinetics studies using levitation
- Underwater and under oil welding
- Welding and joining science
- Welding rod development
- Welding stress management
- Weld metallurgy
- Weld wire development

## Nuclear Materials Research

- Nuclear materials characterization
- Nuclear materials processing
- Nuclear materials properties

## Experimental Methods

- 3D atom probe tomography
- Atomic force microscopy
- Computer modeling and simulation
- Electron microscopy
- Mathematical modeling of material processes
- Nanoindentation
- Non-destructive evaluation
- X-ray diffraction

## Other Research Areas

- Combustion synthesis
- Corrosion science and engineering
- Failure analysis
- Mechanical metallurgy
- Phase transformation and mechanism of microstructural change
- Physical metallurgy
- Reactive metals properties
- Strengthening mechanisms
- Structure-property relationships

## Courses

**MTGN501. MME GRADUATE SEMINAR. 0.5 Semester Hrs.**
(I, II) All full-time MME graduate students must attend the Metallurgical and Materials Engineering seminar. Students must take the Graduate Seminar course every semester that they are enrolled at CSM. At the end of each semester, students are assigned either a satisfactory or unsatisfactory progress grade, based on attendance, until the final semester of the student's degree program, when a letter grade is assigned based on all prior semesters' attendance grades. As a result, while these courses are taken each year, only a maximum of 1.0 hours total of course credit is conferred. Students who have official part-time status are not required to sign up for Graduate Seminar. Attendance of other seminars outside MME can substitute for seminar attendance in MME following course instructor approval. 1 hour lecture; 0.5 hours. Repeatable up to 1 hour.

**MTGN505. CRYSTALLOGRAPHY AND DIFFRACTION. 3.0 Semester Hrs.**

(I) Introduction to point symmetry operations, crystal systems, Bravais lattices, point groups, space groups, Laue classes, stereographic projections, reciprocal lattice and Ewald sphere constructions, the new International Tables for Crystallography, and, finally, how certain properties correlate with symmetry. Subsequent to the crystallography portion, the course will move into the area of diffraction and will consider the primary diffraction techniques (x-rays, electrons and neutrons) used to determine the crystal structure of materials. Other applications of diffraction such as texture and residual stress will also be considered. Prerequisites: Graduate or Senior in good standing. 3 hours lecture, 3 semester hours.

**MTGN511. SPECIAL METALLURGICAL AND MATERIALS ENGINEERING PROBLEMS. 1-3 Semester Hr.**

(I) Independent advanced work, not leading to a thesis. This may take the form of conferences, library, and laboratory work. Selection of assignment is arranged between student and a specific Department faculty-member. Prerequisite: Selection of topic. 1 to 3 semester hours. Repeatable for credit under different titles.

**MTGN512. SPECIAL METALLURGICAL AND MATERIALS ENGINEERING PROBLEMS. 1-3 Semester Hr.**

(II) Continuation of MTGN511. Prerequisite: Selection of topic. 1 to 3 semester hours. Repeatable for credit under different titles.

**MTGN514. DEFECT CHEMISTRY AND TRANSPORT PROCESSES IN CERAMIC SYSTEMS. 3.0 Semester Hrs.**

(I) Ceramic materials science in the area of structural imperfections, their chemistry, and their relation to mass and charge transport; defects and diffusion, sintering, and grain growth with particular emphasis on the relation of fundamental transport phenomena to sintering and microstructure development and control. Prerequisites: DCGN209 or MTGN351; MTGN311. 3 hours lecture; 3 semester hours. (Fall of odd years only.).

**MTGN516. MICROSTRUCTURE OF CERAMIC SYSTEMS. 3.0 Semester Hrs.**

(II) Analysis of the chemical and physical processes controlling microstructure development in ceramic systems. Development of the glassy phase in ceramic systems and the resulting properties. Relationship of microstructure to chemical, electrical, and mechanical properties of ceramics. Application to strengthening and toughening in ceramic composite system. Prerequisite: Graduate status. 3 hours lecture; 3 semester hours. (Spring of even years only.).

**MTGN517. REFRACTORIES. 3.0 Semester Hrs.**

(I) The manufacture, testing, and use of basic, neutral, acid, and specialty refractories are presented. Special emphasis is placed on the relationship between physical properties of the various refractories and their uses in the metallurgical industry. Prerequisite: none. 3 hours lecture; 3 semester hours.

**MTGN518. PHASE EQUILIBRIA IN CERAMIC SYSTEMS. 3.0 Semester Hrs.**

(II) Application of one to four component oxide diagrams to ceramic engineering problems. Emphasis on refractories and glasses and their interaction with metallic systems. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of odd years only.).

**MTGN523. APPLIED SURFACE AND SOLUTION CHEMISTRY. 3.0 Semester Hrs.**

(II) Solution and surface chemistry of importance in mineral and metallurgical operations. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of odd years only.).

**MTGN526. GEL SCIENCE AND TECHNOLOGY. 3.0 Semester Hrs.**

An introduction to the science and technology of particulate and polymeric gels, emphasizing inorganic systems. Interparticle forces. Aggregation, network formation, percolation, and the gel transition. Gel structure, rheology, and mechanical properties. Application to solid-liquid separation operations (filtration, centrifugation, sedimentation) and to ceramics processing. Prerequisite: Graduate Status. 3 hours lecture; 3 semester hours. (Spring of odd years only.).

**MTGN527. SOLID WASTE MINIMIZATION AND RECYCLING. 3.0 Semester Hrs.**

(II) Industrial case-studies, on the application of engineering principles to minimize waste formation and to meet solid waste recycling challenges. Proven and emerging solutions to solid waste environmental problems, especially those associated with metals. Prerequisites: ESGN500 and ESGN504. 3 hours lecture; 3 semester hours.

**MTGN528. EXTRACTIVE METALLURGY OF COPPER, GOLD AND SILVER. 3.0 Semester Hrs.**

Practical applications of fundamentals of chemical-processing-of-materials to the extraction of gold, silver and copper. Topics covered include: History; Ore deposits and mineralogy; Process Selection; Hydrometallurgy and leaching; Oxidation pretreatment; Purification and recovery; Refinement; Waste treatment; and Industrial examples. Prerequisites: Graduate or Senior in good-standing. 3 hours lecture, 3 semester hours.

**MTGN529. METALLURGICAL ENVIRONMENT. 3.0 Semester Hrs.**

(I) Effluents, wastes, and their point sources associated with metallurgical processes, such as mineral concentration and values extraction? providing for an interface between metallurgical process engineering and the environmental engineering areas. Fundamentals of metallurgical unit operations and unit processes, applied to waste and effluents control, recycling, and waste disposal. Examples which incorporate engineering design and cost components are included. Prerequisites: MTGN334. 3 hours lecture; 3 semester hours.

**MTGN530. ADVANCED IRON AND STEELMAKING. 3.0 Semester Hrs.**

(I) Physicochemical principles of gas-slag-metal reactions applied to the reduction of iron ore concentrates and to the refining of liquid iron to steel. The role of these reactions in reactor design?blast furnace and direct iron smelting furnace, pneumatic steelmaking furnace, refining slags, deoxidation and degassing, ladle metallurgy, alloying, and continuous casting of steel. Prerequisite: DCGN209 or MTGN351. 3 hours lecture; 3 semester hours. (Fall of even years only.).

**MTGN531. THERMODYNAMICS OF METALLURGICAL AND MATERIALS PROCESSING. 3.0 Semester Hrs.**

(I) Application of thermodynamics to the processing of metals and materials, with emphasis on the use of thermodynamics in the development and optimization of processing systems. Focus areas will include entropy and enthalpy, reaction equilibrium, solution thermodynamics, methods for analysis and correlation of thermodynamics data, thermodynamic analysis of phase diagrams, thermodynamics of surfaces, thermodynamics of defect structures, and irreversible thermodynamics. Attention will be given to experimental methods for the measurement of thermodynamic quantities. Prerequisite: MTGN351. 3 hours lecture; 3 semester hours.

**MTGN532. PARTICULATE MATERIAL PROCESSING I - COMMINUTION AND PHYSICAL SEPARATIONS. 3.0 Semester Hrs.**
An introduction to the fundamental principles and design criteria for the selection and use of standard mineral processing unit operations in comminution and physical separation. Topics covered include: crushing (jaw, cone, gyratory), grinding (ball, pebble, rod, SAG, HPGR), screening, thickening, sedimentation, filtration and hydrocyclones. Two standard mineral processing plant-design simulation software (MinOCad and JK SimMet) are used in the course. Prerequisites: Graduate or Senior in good- standing. 3 hours lecture, 3 semester hours.

**MTGN533. PARTICULATE MATERIAL PROCESSING II - APPLIED SEPARATIONS. 3.0 Semester Hrs.**
An introduction to the fundamental principles and design criteria for the selection and use of standard mineral processing unit operations in applied separations. Topics covered include: photometric ore sorting, magnetic separation, dense media separation, gravity separation, electrostatic separation and flotation (surface chemistry, reagents selection, laboratory testing procedures, design and simulation). Two standard mineral processing plant-design simulation software (MinOCad and JK SimMet) are used in the course. Graduate or Senior in good-standing. 3 hours lecture, 3 semester hours.

**MTGN534. CASE STUDIES IN PROCESS DEVELOPMENT. 3.0 Semester Hrs.**
A study of the steps required for development of a mineral recovery process. Technical, economic, and human factors involved in bringing a process concept into commercial production. Prerequisite: none. 3 hours lecture; 3 semester hours.

**MTGN535. PYROMETALLURGICAL PROCESSES. 3.0 Semester Hrs.**
(II) Detailed study of a selected few processes, illustrating the application of the principles of physical chemistry (both thermodynamics and kinetics) and chemical engineering (heat and mass transfer, fluid flow, plant design, fuel technology, etc.) to process development. Prerequisite: none. 3 hours lecture; 3 semester hours.

**MTGN536. OPTIMIZATION AND CONTROL OF METALLURGICAL SYSTEMS. 3.0 Semester Hrs.**
Application of modern optimization and control theory to the analysis of specific systems in extractive metallurgy and mineral processing. Mathematical modeling, linear control analysis, dynamic response, and indirect optimum seeking techniques applied to the process analysis of grinding, screening, filtration, leaching, precipitation of metals from solution, and blast furnace reduction of metals. Prerequisite: none. 3 hours lecture; 3 semester hours.

**MTGN537. ELECTROMETALLURGY. 3.0 Semester Hrs.**
(II) Electrochemical nature of metallurgical processes. Kinetics of electrode reactions. Electrochemical oxidation and reduction. Complex electrode reactions. Mixed potential systems. Cell design and optimization of electrometallurgical processes. Batteries and fuel cells. Some aspects of corrosion. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of even years only.).

**MTGN538. HYDROMETALLURGY. 3.0 Semester Hrs.**
(II) Kinetics of liquid-solid reactions. Theory of uniformly accessible surfaces. Hydrometallurgy of sulfide and oxides. Cementation and hydrogen reduction. Ion exchange and solvent extraction. Physicochemical phenomena at high pressures. Microbiological metallurgy. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of odd years only.).

**MTGN539. PRINCIPLES OF MATERIALS PROCESSING REACTOR DESIGN. 3.0 Semester Hrs.**
(II) Review of reactor types and idealized design equations for isothermal conditions. Residence time functions for nonreacting and reacting species and its relevance to process control. Selection of reactor type for a given application. Reversible and irreversible reactions in CSTR?s under nonisothermal conditions. Heat and mass transfer considerations and kinetics of gas-solid reactions applied to fluo-solids type reactors. Reactions in packed beds. Scale up and design of experiments. Brief introduction into drying, crystallization, and bacterial processes. Examples will be taken from current metallurgical practice. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of odd years only.).

**MTGN541. INTRODUCTORY PHYSICS OF METALS. 3.0 Semester Hrs.**
(I) Electron theory of metals. Classical and quantum-mechanical free electron theory. Electrical and thermal conductivity, thermo electric effects, theory of magnetism, specific heat, diffusion, and reaction rates. Prerequisite: MTGN445. 3 hours lecture; 3 semester hours.

**MTGN542. ALLOYING THEORY, STRUCTURE, AND PHASE STABILITY. 3.0 Semester Hrs.**
(II) Empirical rules and theories relating to alloy formation. Various alloy phases and constituents which result when metals are alloyed and examined in detail. Current information on solid solutions, intermetallic compounds, eutectics, liquid immiscibility. Prerequisite: MTGN445 or none. 3 hours lecture; 3 semester hours.

**MTGN543. THEORY OF DISLOCATIONS. 3.0 Semester Hrs.**
(I) Stress field around dislocation, forces on dislocations, dislocation reactions, dislocation multiplication, image forces, interaction with point defects, interpretation of macroscopic behavior in light of dislocation mechanisms. Prerequisite: none. 3 hours lecture; 3 semester hours. (Fall of odd years only.).

**MTGN544. FORGING AND DEFORMATION MODELING. 3.0 Semester Hrs.**
(I) Examination of the forging process for the fabrication of metal components. Techniques used to model deformation processes including slab equilibrium, slip line, upper bound and finite element methods. Application of these techniques to specific aspects of forging and metal forming processes. Prerequisite: none. 3 hours lecture; 3 semester hours. (Fall of odd years only.).

**MTGN545. FATIGUE AND FRACTURE. 3.0 Semester Hrs.**
(I) Basic fracture mechanics as applied to engineering materials, S-N curves, the Goodman diagram, stress concentrations, residual stress effects, effect of material properties on mechanisms of crack propagation. Prerequisite: none. 3 hours lecture; 3 semester hours. (Fall of odd years only.).

**MTGN546. CREEP AND HIGH TEMPERATURE MATERIALS. 3.0 Semester Hrs.**
(II) Mathematical description of creep process. Mathematical methods of extrapolation of creep data. Micromechanisms of creep deformation, including dislocation glide and grain boundary sliding. Study of various high temperature materials, including iron, nickel, and cobalt base alloys and refractory metals, and ceramics. Emphasis on phase transformations and microstructure-property relationships. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of odd years only.).

**MTGN547. PHASE EQUILIBRIA IN MATERIALS SYSTEMS. 3.0 Semester Hrs.**
(I) Phase equilibria of uniary, binary, ternary, and multicomponent systems, microstructure interpretation, pressure-temperature diagrams, determination of phase diagrams. Prerequisite: none. 3 hours lecture; 3 semester hours.

**MTGN548. TRANSFORMATIONS IN METALS. 3.0 Semester Hrs.**
(I) Surface and interfacial phenomena, order of transformation, grain growth, recovery, recrystallization, solidification, phase transformation in solids, precipitation hardening, spinoidal decomposition, martensitic transformation, gas metal reactions. Prerequisite: none. 3 hours lecture; 3 semester hours. (Fall of odd years only.).

**MTGN549. CURRENT DEVELOPMENTS IN FERROUS ALLOYS. 3.0 Semester Hrs.**
(I) Development and review of solid state transformations and strengthening mechanisms in ferrous alloys. Application of these principles to the development of new alloys and processes such as high strength low alloy steels, high temperature alloys, maraging steels, and case hardening processes. Prerequisite: MTGN348. 3 hours lecture; 3 semester hours.

**MTGN551. ADVANCED CORROSION ENGINEERING. 3.0 Semester Hrs.**
(I) Advanced topics in corrosion engineering. Case studies and industrial application. Special forms of corrosion. Advanced measurement techniques. Prerequisite: MTGN451. 3 hours lecture; 3 semester hours. (Fall of even years only.).

**MTGN552. INORGANIC MATRIX COMPOSITES. 3.0 Semester Hrs.**
Introduction to the processing, structure, properties and applications of metal matrix and ceramic matrix composites. Importance of structure and properties of both the matrix and the reinforcement and the types of reinforcement utilized-particulate, short fiber, continuous fiber, and laminates. Emphasis on the development of mechanical properties through control of synthesis and processing parameters. Other physical properties such as electrical and thermal will also be examined. Prerequisite/Co-requisite*: MTGN352, MTGN445/MLGN505*. 3 hours lecture; 3 semester hours. (Summer of even years only.).

**MTGN553. STRENGTHENING MECHANISMS. 3.0 Semester Hrs.**
(II) Strain hardening in polycrystalline materials, dislocation inter actions, effect of grain boundaries on strength, solid solution hardening, martensitic transformations, precipitation hardening, point defects. Prerequisite: MTGN543 or concurrent enrollment. 3 hours lecture;3 semester hours. (Spring of even years only.).

**MTGN554. OXIDATION OF METALS. 3.0 Semester Hrs.**
(II) Kinetics of oxidation. The nature of the oxide film. Transport in oxides. Mechanisms of oxidation. The Oxidation protection of hightemperature metal systems. Prerequisite:none. 3 hours lecture; 3 semester hours. (Spring of even years only.).

**MTGN555. SOLID STATE THERMODYNAMICS. 3.0 Semester Hrs.**
(I) Thermodynamics applied to solid state reactions, binary and ternary phase diagrams, point, line and planar defects, interfaces, and electrochemical concepts. Prerequisite: none. 3 hours lecture; 3 semester hours.

**MTGN556. TRANSPORT IN SOLIDS. 3.0 Semester Hrs.**
(I) Thermal and electrical conductivity. Solid state diffusion in metals and metal systems. Kinetics of metallurgical reactions in the solid state. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of even years only.).

**MTGN557. SOLIDIFICATION. 3.0 Semester Hrs.**
(I) Heat flow and fluid flow in solidification, thermodynamics of solidification, nucleation and interface kinetics, grain refining, crystal and grain growth, constitutional supercooling, eutectic growth, solidification of castings and ingots, segregation, and porosity. Prerequisite: none. 3 hours lecture; 3 semester hours. (Fall of odd years only.).

**MTGN560. ANALYSIS OF METALLURGICAL FAILURES. 3.0 Semester Hrs.**
(II) Applications of the principles of physical and mechanical metallurgy to the analysis of metallurgical failures. Nondestructive testing. Fractography. Case study analysis. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of odd years only.).

**MTGN561. PHYSICAL METALLURGY OF ALLOYS FOR AEROSPACE. 3.0 Semester Hrs.**
(I) Review of current developments in aerospace materials with particular attention paid to titanium alloys, aluminum alloys, and metal-matrix composites. Emphasis is on phase equilibria, phase transformations, and microstructure-property relationships. Concepts of innovative processing and microstructural alloy design are included where appropriate. Prerequisite: none. 3 hours lecture; 3 semester hours. (Fall of even years only.).

**MTGN564. ADVANCED FORGING AND FORMING. 3.0 Semester Hrs.**
(II) Overview of plasticity. Examination and Analysis of working operations of forging, extrusion, rolling, wire drawing and sheet metal forming. Metallurgical structure evolution during working. Laboratory experiments involving metal forming processes. Prerequisites: MTGN445/MLGN505, 2 hours lecture; 3 hours lab, 3 semester hours.

**MTGN565. MECHANICAL PROPERTIES OF CERAMICS AND COMPOSITES. 3.0 Semester Hrs.**
(I) Mechanical properties of ceramics and ceramic-based composites; brittle fracture of solids; toughening mechanisms in composites; fatigue, high temperature mechanical behavior, including fracture, creep deformation. Prerequisites: MTGN445 or MLGN505. 3 hours lecture; 3 semester hours. (Fall of even years only.).

**MTGN569. FUEL CELL SCIENCE AND TECHNOLOGY. 3.0 Semester Hrs.**
Equivalent with CBEN569,MEGN569,MLGN569,
(I) Investigate fundamentals of fuel-cell operation and electrochemistry from a chemical-thermodynamics and materials- science perspective. Review types of fuel cells, fuel-processing requirements and approaches, and fuel-cell system integration. Examine current topics in fuel-cell science and technology. Fabricate and test operational fuel cells in the Colorado Fuel Cell Center. 3 credit hours.

**MTGN570. BIOCOMPATIBILITY OF MATERIALS. 3.0 Semester Hrs.**
Introduction to the diversity of biomaterials and applications through examination of the physiologic environment in conjunction with compositional and structural requirements of tissues and organs. Appropriate domains and applications of metals, ceramics and polymers, including implants, sensors, drug delivery, laboratory automation, and tissue engineering are presented. Prerequisites: BIOL110 or equivalent. 3 hours lecture; 3 semester hours.

**MTGN571. METALLURGICAL AND MATERIALS ENGINEERING LABORATORY. 1-3 Semester Hr.**
Basic instruction in advanced equipment and techniques in the field of extraction, mechanical or physical metallurgy. Prerequisite: Selection. 3 to 9 hours lab ; 1 to 3 semester hours.

**MTGN572. BIOMATERIALS. 3.0 Semester Hrs.**
Equivalent with MLGN572,
(I) A broad overview on materials science and engineering principles for biomedical applications with three main topics: 1) The fundamental properties of biomaterials; 2) The fundamental concepts in biology; 3) The interactions between biological systems with exogenous materials. Examples including surface energy and surface modification; protein adsorption; cell adhesion, spreading and migration; biomaterials implantation and acute inflammation; blood-materials interactions and thrombosis; biofilm and biomaterials-related pathological reactions. Basic principles of bio-mimetic materials synthesis and assembly will also be introduced. 3 hours lecture; 3 semester hours.

**MTGN573. COMPUTATIONAL MATERIALS. 3.0 Semester Hrs.**
(II) Computational Materials is a course designed as an introduction to computational approaches and codes used in modern materials science and engineering, and to provide the hands?on experience in using massively parallel supercomputers and popular materials software packages. The main goal is to provide exposure to students to the growing and highly interdisciplinary field of computational materials science and engineering, through a combination of lectures, hands-on exercises and a series of specifically designed projects. The course is organized to cover different length scales including: atomistic (electronic structure) calculations, molecular dynamics, and phase equilibria modeling. The emerging trends in data driven materials discovery and design are also covered. Particular emphasis is placed on the validation of computational results and recent trends in integrating theory, computations and experiment. Graduate students are expected to successfully complete 4 projects while the undergraduate students are required to finish 3 out of 4 projects. 3 hours lecture; 3 semester hours.

**MTGN580. ADVANCED WELDING METALLURGY. 3.0 Semester Hrs.**
(II) Weldability of high strength steels, high alloys, and light metals; Welding defects; Phase transformations in weldments; Thermal experience in weldments; Pre- and Post-weld heat treatment; Heat affected zone formation, microstructure, and properties; Consumables development. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of odd years only.).

**MTGN581. WELDING HEAT SOURCES AND INTERACTIVE CONTROLS. 3.0 Semester Hrs.**
(I) The science of welding heat sources including gas tungsten arc, gas metal arc, electron beam and laser. The interaction of the heat source with the workpiece will be explored and special emphasis will be given to using this knowledge for automatic control of the welding process. Prerequisite: Graduate Status. 3 hours lecture; 3 semester hours. (Fall of odd years only.).

**MTGN582. MECHANICAL PROPERTIES OF WELDED JOINTS. 3.0 Semester Hrs.**
(II) Mechanical metallurgy of heterogeneous systems, shrinkage, distortion, cracking, residual stresses, mechanical testing of joints, size effects, joint design, transition temperature, fracture. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of odd years only.).

**MTGN583. PRINCIPLES OF NON-DESTRUCTIVE TESTING AND EVALUATION. 3.0 Semester Hrs.**
(I) Introduction to testing methods; basic physical principles of acoustics, radiography, and electromagnetism; statistical and risk analysis; fracture mechanics concepts; design decision making, limitations and applications of processes; fitness-for- service evaluations. Prerequisite: Graduate Status. 3 hours lecture; 3 semester hours. (Fall of odd years only.).

**MTGN584. NON-FUSION JOINING PROCESSES. 3.0 Semester Hrs.**
(II) Joining processes for which the base materials are not melted. Brazing, soldering, diffusion bonding, explosive bonding, and adhesive bonding processes. Theoretical aspects of these processes, as well as the influence of process parameters. Special emphasis to the joining of dissimilar materials using these processes. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of even years only.).

**MTGN586. DESIGN OF WELDED STRUCTURES AND ASSEMBLIES. 3.0 Semester Hrs.**
Introduction to the concepts and analytical practice of designing weldments. Designing for impact, fatigue, and torsional loading. Designing of weldments using overmatching and undermatching criteria. Analysis of combined stresses. Designing of compression members, column bases and splices. Designing of built-up columns, welded plate cylinders, beam-to-column connections, and trusses. Designing for tubular construction. Weld distortion and residual stresses. Joint design. Process consideration in weld design. Welding codes and specifications. Estimation of welding costs. Prerequisite/Co-requisite: MATH225 or equivalent, EGGN320 or equivalent, MTGN475. 3 hours lecture; 3 semester hours. (Summer of odd years only.).

**MTGN587. PHYSICAL PHENOMENA OF WELDING AND JOINING PROCESSES. 3.0 Semester Hrs.**
(I) Introduction to arc physics, fluid flow in the plasma, behavior of high pressure plasma, cathodic and anodic phenomena, energy generation and temperature distribution in the plasma, arc stability, metal transfer across arc, electron beam welding processes, keyhole phenomena. Ohmic welding processes, high frequency welding, weld pool phenomena. Development of relationships between physics concepts and the behavior of specific welding and joining processes. Prerequisite/Co-requisite: PHGN300, MATH225, MTGN475. 3 hours lecture; 3 semester hours. (Fall of even years only.).

**MTGN591. PHYSICAL PHENOMENA OF COATING PROCESSES. 3.0 Semester Hrs.**
(I) Introduction to plasma physics, behavior of low pressure plasma, cathodic and anodic phenomena, glow discharge phenomena, glow discharge sputtering, magnetron plasma deposition, ion beam deposition, cathodic arc evaporation, electron beam and laser coating processes. Development of relationships between physics concepts and the behavior of specific coating processes. Prerequisite/ Co-requisite: PHGN300, MATH225. 3 hours lecture; 3 semester hours. (Fall of odd years only.).

**MTGN593. NUCLEAR MATERIALS SCIENCE AND ENGINEERING. 3.0 Semester Hrs.**
(I) Introduction to the physical metallurgy of nuclear materials, including the nuclear, physical, thermal, and mechanical properties for nuclear materials, the physical and mechanical processing of nuclear alloys, the effect of nuclear and thermal environments on structural reactor materials and the selection of nuclear and reactor structural materials are described. Selected topics include ceramic science of ceramic nuclear material, ceramic processing of ceramic fuel, nuclear reaction with structural materials, radiation interactions with materials, the aging of nuclear materials, cladding, corrosion and the manufacturing of fuels elements. Relevant issues in the modern fuel cycle will also be introduced including nuclear safety, reactor decommissioning, and environmental impacts. Prerequisites: Graduate or Senior in good-standing. 3 hours lecture, 3 semester hours. (Fall of even years only.).

**MTGN598. SPECIAL TOPICS IN METALLURGICAL AND MATERIALS ENGINEERING. 6.0 Semester Hrs.**

(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**MTGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: ?Independent Study? form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/ experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**MTGN605. ADVANCED TRANSMISSION ELECTRON MICROSCOPY. 2.0 Semester Hrs.**

Introduction to transmission electron microscopy techniques and their application to materials characterization. Topics include electron optics, electron-specimen interactions, imaging, diffraction, contrast mechanisms, defect analyses, compositional measurements using energy dispersive x-ray spectroscopy and energy loss spectroscopy, scanning transmission electron microscopy, high angle annular dark field imaging, energy filtered TEM and high resolution phase contrast imaging. Prerequisite: MTGN 505. Co-requisite; MTGN 605L. 2 hours lecture, 2 semester hours.

**MTGN605L. ADVANCED TRANSMISSION ELECTRON MICROSCOPY LABORATORY. 1.0 Semester Hr.**

Specimen preparation techniques and their application to materials characterization. Topics include electron optics, electron-specimen interactions, imaging, diffraction, contrast mechanisms, defect analyses, compositional measurements using energy dispersive x-ray spectroscopy and energy loss spectroscopy, scanning transmission electron microscopy, high angle annular dark field imaging, energy filtered TEM and high resolution phase contrast imaging. Prerequisite: Concurrent enrollment in MTGN 605. 3 hours lab, 1 semester hour.

**MTGN631. TRANSPORT PHENOMENA IN METALLURGICAL AND MATERIALS SYSTEMS. 3.0 Semester Hrs.**

Physical principles of mass, momentum, and energy transport. Application to the analysis of extraction metallurgy and other physicochemical processes. Prerequisite: MATH225 and MTGN461 or equivalent. 3 hours lecture; 3 semester hours.

**MTGN671. ADVANCED MATERIALS LABORATORY. 1-3 Semester Hr.**

(I) Experimental and analytical research in the fields of production, mechanical, chemical, and/or physical metallurgy. Prerequisite: none. 1 to 3 semester hours; 3 semester hours.

**MTGN672. ADVANCED MATERIALS LABORATORY. 1-3 Semester Hr.**

(II) Continuation of MTGN671. 1 to 3 semester hours.

**MTGN696. VAPOR DEPOSITION PROCESSES. 3.0 Semester Hrs.**

(II) Introduction to the fundamental physics and chemistry underlying the control of deposition processes for thin films for a variety of applications? wear resistance, corrosion/oxidation resistance, decorative coatings, electronic and magnetic. Emphasis on the vapor deposition process varia - bles rather than the structure and properties of the deposited film. Prerequisites: MTGN351, MTGN461, or equivalent courses. 3 hours lecture; 3 semester hours. (Summer of odd years only.).

**MTGN697. MICROSTRUCTURAL EVOLUTION OF COATINGS AND THIN FILMS. 3.0 Semester Hrs.**

(I) Introduction to aqueous and non-aqueous chemistry for the preparation of an effective electrolyte; for interpretation of electrochemical principles associated with electrodeposition; surface science to describe surface structure and transport; interphasial structure including space charge and double layer concepts; nucleation concepts applied to electrodeposition; electrocrystallization including growth concepts; factors affecting morphology and kinetics; co-deposition of non-Brownian particles; pulse electrodeposition; electrodeposition parameters and control; physical metallurgy of electrodeposits; and, principles associated with vacuum evaporation and sputter deposition. Factors affecting microstructural evolution of vacuum and sputtered deposits; nucleation of vapor and sputtered deposits; modeling of matter-energy interactions during co-deposition; and, Thornton?s model for coating growth. Prerequisite/ co-requisite: MATH225, MTGN351, MTGN352. 3 hours lecture; 3 semester hours. (Summer of even years only.).

**MTGN698. SPECIAL TOPICS IN METALLURGICAL AND MATERIALS ENGINEERING. 6.0 Semester Hrs.**

(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**MTGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: ?Independent Study? form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/ experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**MTGN700. GRADUATE RESEARCH CREDIT: MASTER OF ENGINEERING. 1-6 Semester Hr.**

(I, II, S) Research credit hours required for completion of the degree Master of Engineering. Research under the direct supervision of a faculty advisor. Credit is not transferable to any 400, 500, or 600 level courses. However, MTGN 705 credit hours may be transferred, in accordance with the requirements for this (M.E.) degree, by a Master of Science graduate-student who previously accumulated these credit-hours and subsequently opted to change their degree program to a Master of Engineering. Repeatable for credit. Variable: 1 to 6 semester hours.

**MTGN707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**

(I, II, S) Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

## Professors

Amy Clarke

Kip O. Findley

Brian P. Gorman

Michael J. Kaufman, Director of the Center for Advanced Non-Ferrous Structural Alloys

Jeffrey C. King

Suveen N. Mathaudhu

Ryan O'Hayre

Ivar E. Reimanis, Department Head, Herman F. Coors Distinguished Professor of Ceramics

Angus A. Rockett

John G. Speer, American Bureau of Shipping Endowed Chair in Metallurgical and Materials Engineering

## Associate Professors

Geoff L. Brennecka, Director of the Colorado Center for Advanced Ceramics, co-Director of the Alliance for the Development of Additive Processing Technologies (ADAPT)

Kester Clarke, FIERF Professor

Emmanuel De Moor

Jeffrey C. King

Corinne E. Packard

Vladan Stevanovic

Zhenzhen Yu

## Assistant Professors

Megan Holtz

Jonah Klemm-Toole

## Teaching Professor

Gerald Bourne, Assistant Department Head

## Research Faculty

Lawrence Cho

Robert Cryderman

Arun Devaraj

David Diercks

Prashun Gorai

Peter Green

Terry Lowe

Stephen Midson

Michael Sanders

Sridhar Seetharaman

Andriy Zakutayev

## Affiliate Faculty

Corby G. Anderson

Grover Coors

Adam Creuziger

C. Matthew Enloe

Ron Goldfarb

Juan Carlos Madeni

Erik Spiller

Patrick R. Taylor

Terry Totemeier

James C. Williams

## Professors Emeriti

Glen R. Edwards, University Professor Emeritus

John P. Hager, University Professor Emeritus

George Krauss, University Professor Emeritus

Stephen Liu, University Professor Emeritus, Inaugural American Bureau of Shipping Chair Professor

Gerard P. Martins, Professor Emeritus

David K. Matlock, University Professor Emeritus

Brajendra Mishra, University Professor Emeritus

John J. Moore, Professor Emeritus

David L. Olson, University Professor Emeritus

Dennis W. Readey, University Professor Emeritus

Chester J. Van Tyne, Professor Emeritus

## Associate Professors Emeriti

Gerald L. DePoorter

Robert H. Frost

Steven W. Thompson