The Department of Materials Science and Engineering engages faculty, students, postdoctoral researchers, engineers, and staff in developing and understanding relationships between processing, structure, properties, and the performance of materials in engineering applications. The Department provides a research-intensive environment that encourages collaboration and underpins modern education of undergraduate and graduate students as well as professionals in the field. This environment provides a strong foundation for advancing the frontiers of materials research, developing important technical innovations, and preparing engineers and scientists for challenging leadership careers.
materials courses, which also allow students to choose one of several areas of concentration within the major. A total of 129 credit hours is required.

The Bachelor of Science degree program in Materials Science and Engineering is accredited by the Engineering Accreditation Commission of ABET, www.abet.org (http://www.abet.org).

Throughout the undergraduate curriculum in materials science and engineering, scientific fundamentals are integrated with coverage of current manufacturing, design, and applications of engineering materials. The goal of the Department of Materials Science and Engineering is to prepare students for rewarding careers that provide creative, effective solutions to societal needs, through coursework and associated activities that emphasize:

• The interrelationships among the processing, structure, properties, and performance of engineering materials
• The mutual reinforcement of education and professional development throughout one’s career.

The undergraduate experience in Materials Science and Engineering at Case Western Reserve is marked by a high degree of hands-on experience and many opportunities for professional development before graduation. Lab courses, senior projects, and plant tours ensure that every student sees the field first-hand in current research and industrial settings.

Program Educational Objectives
1. Graduates will take an active part in professional organizations.
2. Graduates will assume leadership positions in materials science related industries.
3. Graduates will be effectively involved in solving technical problems.
4. Graduates may successfully enter and complete graduate and professional degree programs.

Student Outcomes
As preparation for achieving the above educational objectives, the BS degree program in Materials Science and Engineering is designed so that students attain:

• an ability to apply knowledge of mathematics, science, and engineering
• an ability to design and conduct experiments, as well as to analyze and interpret data
• an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
• an ability to function on multi-disciplinary teams
• an ability to identify, formulate, and solve engineering problems
• an understanding of professional and ethical responsibility
• an ability to communicate effectively
• the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
• a recognition of the need for, and an ability to engage in life-long learning
• a knowledge of contemporary issues
• an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Bachelor of Science in Engineering
Required Courses for Major in Materials Science and Engineering
In addition to Engineering Core (http://bulletin.case.edu/undergraduatestudies/csedegree) and CWRU General Education (http://bulletin.case.edu/undergraduatestudies/degreeprograms) requirements, the major requires the following courses.

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMSE 110</td>
<td>Transitioning Ideas to Reality I - Materials in Service of Industry and Society</td>
<td>1</td>
</tr>
<tr>
<td>EMSE 120</td>
<td>Transitioning Ideas to Reality II - Manufacturing Laboratory</td>
<td>2</td>
</tr>
<tr>
<td>EMSE 220</td>
<td>Materials Laboratory I</td>
<td>2</td>
</tr>
<tr>
<td>EMSE 228</td>
<td>Mathematical Methods for Materials Science and Engineering</td>
<td>3</td>
</tr>
<tr>
<td>EMSE 276</td>
<td>Materials Properties and Design</td>
<td>3</td>
</tr>
<tr>
<td>EMSE 319</td>
<td>Processing and Manufacturing of Materials</td>
<td>3</td>
</tr>
<tr>
<td>EMSE 320</td>
<td>Materials Laboratory II</td>
<td>1</td>
</tr>
<tr>
<td>EMSE 327</td>
<td>Thermodynamic Stability and Rate Processes</td>
<td>3</td>
</tr>
<tr>
<td>EMSE 328</td>
<td>Meso-scale Science Including Nanotechnology</td>
<td>3</td>
</tr>
<tr>
<td>EMSE 330</td>
<td>Materials Laboratory III</td>
<td>2</td>
</tr>
<tr>
<td>EMSE 343</td>
<td>Materials for Electronics and Photonics</td>
<td>3</td>
</tr>
<tr>
<td>EMSE 345</td>
<td>Materials for Biological and Medical Technology</td>
<td>3</td>
</tr>
<tr>
<td>EMSE 349</td>
<td>Materials for Energy and Sustainability</td>
<td>3</td>
</tr>
<tr>
<td>EMSE 372</td>
<td>Structural Materials by Design</td>
<td>4</td>
</tr>
<tr>
<td>EMSE 379</td>
<td>Design for Lifetime Performance</td>
<td>3</td>
</tr>
<tr>
<td>EMSE 398</td>
<td>Senior Project in Materials I</td>
<td>1</td>
</tr>
<tr>
<td>EMSE 399</td>
<td>Senior Project in Materials II</td>
<td>2</td>
</tr>
</tbody>
</table>

Total Units: 48

Concentrations
The undergraduate program includes courses that expose students to greater depth in areas related to materials science and engineering. These concentration sequences are of two types:

• Students may select an area of concentration that is based on an application or subfield of engineering materials. Each concentration will be a coherent set of courses that, in conjunction with one or more of the courses already required for all EMSE majors plus a specified mathematics/natural science/statistics course, will provide significant depth in an area of materials specialization.
• Students also have the option of designing a concentration — Advanced Materials Science and Engineering — in consultation
with their advisors and subject to approval by the department’s Undergraduate Studies Committee.

The proposed concentrations are below. All concentrations equal 12 credit hours (four courses).

### Biomaterials

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBME 201</td>
<td>Physiology-Biophysics I *</td>
<td>3</td>
</tr>
<tr>
<td>EBME 202</td>
<td>Physiology-Biophysics II *</td>
<td>3</td>
</tr>
</tbody>
</table>

Plus two of the following:

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBME/EMAC 303</td>
<td>Structure of Biological Materials</td>
</tr>
<tr>
<td>EBME 305</td>
<td>Materials for Prosthetics and Orthotics</td>
</tr>
<tr>
<td>EBME 306</td>
<td>Introduction to Biomedical Materials</td>
</tr>
<tr>
<td>EBME 316</td>
<td>Biomaterials for Drug Delivery</td>
</tr>
<tr>
<td>EBME 325</td>
<td>Introduction to Tissue Engineering</td>
</tr>
<tr>
<td>EBME 406/EMAC 471</td>
<td>Polymers in Medicine</td>
</tr>
</tbody>
</table>

**EBME/EECS 480B** The Human Body

### Electronic Materials

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYS 221</td>
<td>Introduction to Modern Physics *</td>
<td>3</td>
</tr>
</tbody>
</table>

Plus three of the following (from either or both categories):

- Emphasis on solid state physics:
  - PHYS 315 | Introduction to Solid State Physics |
  - PHYS 326 | Physical Optics |
  - PHYS 327 | Laser Physics |
  - PHYS 331 | Introduction to Quantum Mechanics I |

- Emphasis on electronic device technology:
  - CHEM 340 | Solar Energy Conversion |
  - ECHE 383 | Chemical Engineering Applied to Microfabrication and Devices |
  - EECS 309 | Electromagnetic Fields I |
  - EECS 321 | Semiconductor Electronic Devices |
  - EECS 322 | Integrated Circuits and Electronic Devices |
  - EMSE 405 | Dielectric and Electrical Properties of Materials |
  - EMSE 427 | Dislocations in Solids |
  - EMSE 463 | Magnetism and Magnetic Materials |

**EMAC 375** Fundamentals of Non-Newtonian Fluid Mechanics and Polymer Rheology

**EMAC 377** Polymer Processing

Completion of this concentration (including EMAC 276 and EMAC 376, as required for the major in Materials Science and Engineering) satisfies the requirements for a minor in Polymer Science and Engineering.

### Structural Materials and Mechanical Behavior

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>STAT 312</td>
<td>Basic Statistics for Engineering and Science *</td>
<td>3</td>
</tr>
</tbody>
</table>

Plus three of the following:

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECIV 211</td>
<td>Civil Engineering Materials</td>
</tr>
<tr>
<td>ECIV 310</td>
<td>Strength of Materials</td>
</tr>
<tr>
<td>EMAE 370</td>
<td>Design of Mechanical Elements</td>
</tr>
<tr>
<td>EMAE 378</td>
<td>Mechanics of Machinery I</td>
</tr>
<tr>
<td>EMSE 417</td>
<td>Properties of Materials in Extreme Environments</td>
</tr>
<tr>
<td>EMSE 421</td>
<td>Fracture of Materials</td>
</tr>
<tr>
<td>EMSE 422</td>
<td>Failure Analysis</td>
</tr>
<tr>
<td>EMSE 427</td>
<td>Dislocations in Solids</td>
</tr>
<tr>
<td>EMAE 480</td>
<td>Fatigue of Materials</td>
</tr>
</tbody>
</table>

- Satisfies the Mathematics/Science/Statistics requirement of the Case School of Engineering.

### Advanced Materials Science and Engineering

Students may satisfy the concentration requirement by taking nine credits of courses from engineering, math, statistics, or natural sciences departments (beyond those specifically required in the curriculum) at the 300 level or above, plus a course to satisfy the Mathematics/Natural Sciences/Statistics requirement in the Engineering Core. The courses are to be selected in consultation with the student’s advisor and will be subject to approval by the department’s Undergraduate Studies Committee. This option is appropriate for students who desire further study in topics relevant to materials science and engineering that are not represented in the four specializations listed above.

### Bachelor of Science in Engineering

#### Suggested Program of Study: Major in Materials Science and Engineering

The following is a suggested program of study. Current students should always consult their advisers and their individual graduation requirement plans as tracked in SIS (http://sis.case.edu).

**First Year**

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAGES</td>
<td>First year Seminar *</td>
<td>4</td>
</tr>
<tr>
<td>PHED 1xx</td>
<td>Physical Education Activities *</td>
<td></td>
</tr>
</tbody>
</table>

**Calculus for Science and Engineering I (MATH 121)**

**Principles of Chemistry for Engineers (CHEM 111)**

**Elementary Computer Programming (ENGR 131)**

**General Physics I - Mechanics (PHYS 121)**

**or Physics and Frontiers I - Mechanics (PHYS 123)**
<table>
<thead>
<tr>
<th>Semester</th>
<th>Units</th>
<th>Fall</th>
<th>Spring</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Second Year</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General Physics II - Electricity and Magnetism (PHYS 122)** or Physics and Frontiers II - Electricity and Magnetism (PHYS 124)</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials Properties and Design (EMSE 276)</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAGES University Seminar 2*</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calculus for Science and Engineering III (MATH 223)** or Calculus III (MATH 227)</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humanities/Social Science I**</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elementary Differential Equations (MATH 224)** or Differential Equations (MATH 228)</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Statics and Strength of Materials (ENGR 200)**</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials Laboratory I (EMSE 220)</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mathematical Methods for Materials Science and Engineering (EMSE 228)</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polymer Properties and Design (EMAC 276)</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Year Total:</strong> 16</td>
<td>17</td>
<td></td>
<td></td>
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<tr>
<td><strong>Third Year</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials for Electronics and Photonics (EMSE 343)</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humanities/Social Science II**</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Introduction to Circuits and Instrumentation (ENGR 210)**</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials Laboratory II (EMSE 320)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structural Materials by Design (EMSE 372)</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentration IIa</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermodynamics, Fluid Dynamics, Heat and Mass Transfer (ENGR 225)**</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials Laboratory III (EMSE 330)</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processing and Manufacturing of Materials (EMSE 319)</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermodynamic Stability and Rate Processes (EMSE 327)</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Professional Communication for Engineers (ENGL 398) &amp; Professional Communication for Engineers (ENGR 398)**</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Year Total:</strong> 15</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fourth Year</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentration IVa</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Total Units in Sequence:** 129

**Hours required for graduation:** 129

- University general education requirement
- Engineering general education requirement
- Actual courses and sequence will vary depending on the concentration chosen; see "Concentrations."
- This requirement may also be met by a minimum of two credits selected from EMAE 160 (3), EMSE 125 or EMSE 325.

**Cooperative Education** (http://engineering.case.edu/coop)

Opportunities are available for students to alternate studies with work in industry or government as a co-op student, which involves paid full-time employment over seven months (one semester and one summer). Students may work in one or two co-ops, beginning in the third year of study. Co-ops provide students the opportunity to gain valuable hands-on experience in their field by completing a significant engineering project while receiving professional mentoring. During a co-op placement, students do not pay tuition, but maintain their full-time student status while earning a salary. Learn more at engineering.case.edu/coop. Alternatively or additionally, students may obtain employment as summer interns.

**Five-Year Combined BS/MS Program**

This program offers outstanding undergraduate students the opportunity to obtain an MS degree, with a thesis, in one additional year of study beyond the BS degree. (Normally, it takes two years beyond the BS to earn an MS degree.) In this program, an undergraduate student can take up to 9 credit hours that simultaneously satisfy undergraduate and graduate requirements. Students considering the combined BS/MS Program should use the Advanced Materials Science concentration, and should select their concentration in consultation with their departmental academic advisor. Typically, students in this program start their research leading to the MS thesis in the fall semester of the senior year. The BS degree is awarded at the completion of the senior year.

Application for admission to the five year BS/MS program is made after completion of five semesters of course work. Minimum requirements are a 3.2 grade point average and the recommendation of a faculty member of the department. Interested students should contact Professor Peter Lagerlöf. Review the Office of Undergraduate Studies BS/MS program
requirements here (http://bulletin.case.edu/undergraduatestudies/gradprofessional/#accelerationtowardgraduatedegreetext).

Minor in Materials Science and Engineering

In addition to the Bachelor of Science degree program in materials science and engineering, the department also offers a minor in materials science and engineering. This sequence is intended primarily for a student majoring in science or engineering, but it is open to any student with a sound background in introductory calculus, chemistry, and physics. This program requires the completion of EMSE 276 Materials Properties and Design and a minimum of 12 additional credit hours of EMSE courses, including no more than 3 credits of EMSE 125 Freshman Research in Materials Science and Engineering and EMSE 325 Undergraduate Research in Materials Science and Engineering, and no more than 6 credits of one- or two-credit courses. Professor Mark DeGuire (mark.deguire@case.edu) (510 White, 368.4221) will assist EMSE minors with course selection.

Minor in Applied Data Science

This undergraduate Minor in Applied Data Science (ADS), based in the Case School of Engineering, is available as a minor to students across CWRU. The minor is directed to students studying in the domains of Engineering and Physical Sciences (including Energy and Manufacturing, Astronomy, Geology, Physics), Health (including Translational and Clinical), and Business (including Finance, Marketing, and Economics). Successful completion of the ADS minor requirements leads to a "Minor in Applied Data Science" for the graduating student. The ADS minor represents that the students have developed knowledge of the essential elements of Data Science and Analytics in the area of their major (their domain of expertise).

Elements of the ADS minor:
The minor is structured so that the students who qualify for the minor have a working understanding of the basic ADS tools and their application in their domain area. This includes:

- 1. Data Management: datastore, sources, streams;
- 2. Distributed Computing: local computer, distributed computing such as Hadoop or other cloud computing;
- 3. Informatics, Ontology, Query: including search, data assembly, annotation; and
- 4. Statistical Analytics: tools such as R statistics and high level scripting languages (such as Python).

The data types found in these domains are diverse. They include time series and spectral data for Energy and Astronomy, and sensor and production data and image and volumetric data for Manufacturing. In Health, Translational ADS includes Genomic, Proteomic and other Omics data, while Clinical ADS includes patient data, medical data, physiological time series, and mobile data. Business data types include stock and other financial market data for Finance, time series and cross section data for Economics, and operations and consumer behavior data for Marketing.

Students will develop comprehensive experience in the steps of data analysis. Can the steps be formatted as a bulleted or numbered list?

- Step 1: define the ADS questions, and
- Step 2: identify, locate, and/or generate the necessary data, including defining the ideal data set and variables of interest, determining and obtaining accessible data and cleaning the data in preparation for analysis.
- Step 3: exploratory data analysis to start identifying the significant characteristics of the data and information it contains.
- Step 4: statistical modeling and prediction, including interpretation of results, challenging results, and developing insights and actions.
- Step 5: synthesizing the results in the context of the domain and the initial questions, and writing this up.
- Step 6: the creation of reproducible research, including code, datasets, documentation and reports, which are easily transferable and verifiable.

The ADS minor curriculum

The curriculum is based on five 3-credit courses, with one class chosen from each of Levels 1 through Level 5, which cover the spectrum of learning needed to achieve domain area expertise in data science and analytics. The courses are chosen to be both cross-cutting, i.e., intermixing students from across the university in the fundamental ADS concepts such as scripting and statistics (Levels 1, 2, and 4), and domain-focused (Levels 3 and 5). For the Level 4 undergraduate research course, the research topic will be approved by the ADS minor advisor, and will also be a 3-credit project. This will provide ADS minor students both the domain focused ADS learning they need, and a broadening perspective on applications, methods, and uses of ADS in other domains.

Courses Counted Toward ADS Minor Requirements

Established courses included in the ADS Minor are found in Case School of Engineering (Materials Science, Electrical Engineering and Computer Science, Manufacturing), CAS (Mathematics, Astronomy, Philosophy); SOM, SON, and WSOM (Marketing, Finance, Operations, and Economics).

The courses that meet the requirements for the ADS Minor can also be taken by students to meet requirements in Major programs, and therefore serve a dual purpose in our academic offerings. However, each program, department and school may have its own criteria on whether a given course could be "double counted" towards major and minor requirements.

Level 5:

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAFI 361</td>
<td>Applied Financial Analytics</td>
<td>3</td>
</tr>
<tr>
<td>ECON 327</td>
<td>Advanced Econometrics</td>
<td>3</td>
</tr>
<tr>
<td>MKMR 308</td>
<td>Measuring Marketing Performance</td>
<td>3</td>
</tr>
<tr>
<td>MKMR 310</td>
<td>Marketing Analytics</td>
<td>3</td>
</tr>
<tr>
<td>SYBB 459</td>
<td>Bioinformatics for Systems Biology</td>
<td>3</td>
</tr>
</tbody>
</table>

Level 4:

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTR 369</td>
<td>Undergraduate Research</td>
<td>1-3</td>
</tr>
<tr>
<td>DSCI 352</td>
<td>Applied Data Science Research</td>
<td>3</td>
</tr>
<tr>
<td>EMSE 325</td>
<td>Undergraduate Research in Materials Science and Engineering</td>
<td>1-3</td>
</tr>
<tr>
<td>SYBB 387</td>
<td>Undergraduate Research in Systems Biology</td>
<td>1-3</td>
</tr>
</tbody>
</table>

Level 3:

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSCI 351</td>
<td>Exploratory Data Science</td>
<td>3</td>
</tr>
<tr>
<td>MKMR 201</td>
<td>Marketing Management</td>
<td>3</td>
</tr>
</tbody>
</table>
The M.S. degree in Materials Science and Engineering is awarded through the Department of Materials Science and Engineering (DMSE) at Case Western Reserve University (CWRU). The programs address: structure-property relationships; processing methodologies; comprehensive characterization; theory, computational methods and analytics; and engineering behavior of a broad array of materials and material systems.

**MS Degree Requirements**

The M.S. degree in Materials Science and Engineering is awarded through either the Master's Thesis (Plan A) or Master's Comprehensive (Plan B). Both require a total of 27 credit hours distributed between courses and independent research. Plan A involves a thesis based on individual research, totaling no fewer than 9 credit hours, with a final oral defense; this plan is appropriate for full-time graduate students. Plan B involves a major project, typically 3 credit hours and completed in a single semester, and a final comprehensive oral exam; this route is usually followed by part-time graduate students who are currently employed as materials engineers. The examining committee consists of three faculty members of the department for either Plan A or Plan B. Additional committee members may be added at the discretion of the student in consultation with his or her advisor.

Plan A requires successful completion of 6 courses (18 credit hours) and at least 9 credit hours of EMSE 651 (Thesis M.S.). Plan B requires the successful completion of 8 courses (24 credit hours) as well as 3 credit hours of EMSE 649 (Special Projects).

A Planned Program of Study (PPOS) must be submitted by the end of the second semester for Plan A and for Plan B students. The PPOS should be prepared by the student and his/her advisor and submitted online to the School of Graduate Studies.

**Accelerated 1-Year M.S. in Materials Science and Engineering with a focus on data science**

Materials science and engineering is a discipline that extends from the basic science of materials micro-structure and properties to the design and evaluation of materials in engineering systems. Data science and analytics seeks to identify statistically significant relationships, model development, and predictive behavior of large data sets generated by e.g. manufacturing technologies. This suggested course of study, which extends classical education in materials science and engineering with data science and analytics, can be completed in one calendar year.

The Department of Materials Science and Engineering (DMSE) at Case Western Reserve University (CWRU) is a research-centered educational environment whose mission is to enhance the productivity, quality, and benefit of materials-related learning to its students, faculty, and community. DMSE bears a commitment to the improvement of materials technology, DMSE is equipped with state-of-the-art facilities for mechanical characterization as well as micro-characterization of materials (conventional and advanced methods of electron microscopy and spatially resolved surface analysis). The synergy of these facilities and applying them to a broad spectrum of cutting-edge materials research consistently thrust us among the top tiers of materials research institutions in the nation.

The suggested course of study includes nine (9) courses taken over three semesters: Fall Semester, Spring Semester and Summer Semester.


**PhD Degree Requirements**

Immediately upon entering the department, the Ph.D. candidate normally will:

- Fill out and submit the first part of the Planned Program of Study (PPOS) & Supplementary Form
- Register for 2 classes during the first semester
• Register for EMSE 701 Dissertation Ph.D. (usually 3 credit hours) during the first semester. Note that registration for EMSE 701 is not permitted before the Planned Program of Study form is turned in.

As specified in the University General Bulletin section of the School of Graduate Studies: “In order to meet the requirements for the doctorate, a student must pass satisfactorily a general examination (or a series of examinations covering different fields) specified and administered by the student’s department or supervising committee.”

Candidates for a Ph.D. degree in Materials Science and Engineering must pass a two-part General Exam. The first part is a Comprehensive Exam and the second part is a Thesis Proposal Evaluation. A cumulative GPA of 3.0 or higher for courses taken at Case Western Reserve University is required to register to take the Comprehensive Exam.

**PhD Comprehensive Exam**

Full-time students entering with an M.S. degree are required to take the Ph.D. Comprehensive Exam within one year. Full-time students entering with a B.S. degree must take the Ph.D. Comprehensive Exam within two years of entering the Ph.D. program. Part-time students must complete the exam prior to accumulating ten or more credit hours. The exam will be offered twice per year at roughly six-month intervals, typically in January and June. The exam will consist of a written test covering specific areas of materials science and engineering.

The exam has multi-part questions that cover the following four areas:

1. Structure (EMSE 503)
2. Thermodynamics (EMSE 504)
3. Phase Transformations (EMSE 505)
4. A Synthesis Area: which combines concepts from the first three areas as they apply to performance of materials Functional Materials..

Students who achieve a score of 70 or above on three of the completed questions and an overall average of 75 or above will pass outright. Students who do not achieve this on their first attempt of the written exam will have one more opportunity to take the Comprehensive Exam the next time the department offers it.

**Thesis Proposal Evaluation**

The Thesis Proposal Evaluation must occur in the semester immediately following the successful completion of the Ph.D. Comprehensive Exam unless a petition, supported by their research advisor, is approved by the graduate studies committee. The Thesis Proposal Evaluation tests the more specific knowledge of the Ph.D. candidate concerning the science underlying the proposed research and the candidate’s intellectual maturity. It is composed of a written and an oral evaluation, both dealing with the candidate’s proposed research project and specialized courses taken in support of their research program. Both should include a literature search, analysis of the research problem, suggested research procedures, and the general results to be expected. The student’s dissertation advisory committee will examine the document for this purpose. The written document must be submitted to the student’s dissertation advisory committee at least one week prior to the oral evaluation. Both parts of the Thesis Proposal Evaluation will be graded Pass/Fail.

Upon passing both the Comprehensive Exam and the Thesis Proposal Evaluation, a student will advance to Ph.D. Candidacy.

**PhD Program of Study (Course Requirements)**

A Ph.D. student must take a minimum of 18 credit hours of EMSE 701 and must continue registration each subsequent regular semester (Fall and Spring) until the dissertation is complete, unless granted a leave of absence. The time limit for the Ph.D. program is 5 years for full-time students, starting with the first semester of EMSE 701 registration.

The minimum course requirement for a Ph.D. degree is 12 courses (36 credit hours) beyond the B.S. level, out of which at least 6 courses (18 credit hours) must be taken at Case Western Reserve University. Of these 12 courses, 4 courses must satisfy the Breadth Requirement and 2 courses must satisfy the Basic Science Requirement for the department as outlined below. In the case of a student entering with a M.S. degree from another discipline, additional courses may be required at the discretion of the student’s academic advisor. A GPA of 3.0 is required for graduation. Students with a cumulative GPA below 3.0 will be placed on academic probation.

**MSE Core Sequence**: The Materials Science and Engineering Core sequence consists of:

- EMSE 503 Structure of Materials
- EMSE 504 Thermodynamics of Solids
- EMSE 505 Phase Transformation, Kinetics, and Microstructure

The Core is a required part of the Program of Study for all Ph.D. students. Transfer credit for comparable graduate courses taken at another institution will be allowed on a case-by-case basis. Students may find it helpful to complete the core sequence prior to taking the Ph.D. comprehensive exam.

**Breadth Requirement**: The Breadth Requirement for the Ph.D. can be fulfilled by taking a total of 4 courses (12 credit hours) within the Case School of Engineering selected in consultation with the student’s advisor.

**Basic Science Requirements**: A minimum depth in basic science of 2 courses (6 credit hours) is required for a Ph.D. degree. This requirement can be fulfilled by taking 2 courses at the 400 or 500 level selected from Physics, Chemistry, Biology, Mathematics and/or Statistics, and/or certain engineering curricula approved by the department Graduate Studies Committee. Engineering courses used to meet this requirement must be approved prior to enrolling in the course (the deadline being the conclusion of add/drop in any given semester). Students making such a request are required to submit a petition to the department graduate studies committee that justifies the role of the stipulated course as basic, rather than applied, science. Such petitions are expected to be brief. Courses that are not approved as meeting the basic science requirement may be applicable to the breadth requirement.

The PPOS, a list of the courses the student will take to fulfill the Ph.D. requirements, will be discussed and updated if needed at the time of the Thesis Proposal Evaluation.

Upon successful completion of all requirements and research, the Ph.D. candidate must submit a written dissertation as evidence for their ability to conduct independent research at an advanced level. The Ph.D. candidate must pass a final oral exam in defense of the dissertation. The dissertation committee must consist of at least three faculty members from the department and one non-departmental member. The candidate must provide each committee member with a copy of the completed dissertation at least 10 days before the exam, so that the committee members may have an opportunity to read and discuss it in advance.
Facilities

Materials Processing

The department's processing laboratories include facilities which permit materials processing from the liquid state (casting) as well as in the solid state (powder processing). The department has its own foundry that houses mold making capabilities (green and bonded sand, permanent mold, and investment casting), induction melting furnaces of various capabilities for air melting of up to 1500 pounds of steel, electrical resistance furnaces for melting and casting up to 800 pounds of aluminum, and 500 pounds of magnesium under protective atmosphere, a dual chamber vacuum induction melting unit with a capacity of up to 30 pounds of superalloys, a 350 ton squeeze casting press, and state-of-the-art thermal fatigue testing and characterization equipment. The Crystal Growth Laboratory has facilities for production of high purity electronic single crystals using a variety of furnaces with the additional capability of solidifying under large magnetic fields. In addition, a CVD and MOCVD reactor has been set up to do research on the growth of SiC and GaN on Si, sapphire, and other substrates. Secondary processing and working can be accomplished using a high-speed hot and cold rolling mill, swaging units, and a state-of-the-art hydrostatic extrusion press. The department has heat treatment capabilities including numerous box, tube, and vacuum furnaces. For the processing of powder metals or ceramics the department possesses a 300,000 pound press, a vacuum hot press (with capabilities of up to 7 ksi and 2300 C), a hot isostatic press (2000 C and 30 ksi), a 60 ksi wet base isostatic press, and glove boxes. Sintering can be performed in a variety of controlled atmospheres while a microcomputer-controlled precision dilatometer is available for sintering studies. Several ball mills, shaker mills, and a laboratory model attritor are also available for powder processing. In addition, facilities are available for sol-gel processing, glass melting, and diamond machining; a spray dryer is available for powder granulation.

A Deformation Processing Laboratory has recently been commissioned that contains two dual hydraulic MTS presses. The first press is designed to evaluate the stretching and drawing properties of materials in sheet form. Its maximum punch and hold down forces are 150,000 each. Its maximum punch velocity is 11.8 inch/sec. The second press is designed to evaluate the plastic flow behavior of materials in an environment that simulates modern manufacturing processing. The press can deliver up to five consecutive impacts to a material in less than five seconds with a punch velocity as high as 110 inch/sec. The maximum punch force is 110,000 pounds.

Advanced Manufacturing and Mechanical Reliability Center (AMMRC)

The Advanced Manufacturing and Mechanical Reliability Center (AMMRC) permits the determination of mechanical behavior of materials over loading rates ranging from static to impact, with the capability of testing under a variety of stress states under either monotonic or cyclic conditions. A variety of furnaces and environmental chambers are available to enable testing at temperatures ranging from -196 C to 1800 C. The facility is operated under the direction of a faculty member and under the guidance of a full-time engineer. The facility contains one of the few laboratories in the world for high-pressure deformation and processing, enabling experimentation under a variety of stress states and temperatures. The equipment in this state-of-the-art facility includes:

**High Pressure Deformation Apparatus:** These units enable tension or compression testing to be conducted under conditions of high hydrostatic pressure. Each apparatus consists of a pressure vessel and diagnostics for measurement of load and strain on deforming specimens, as well as instantaneous pressure in the vessel. Pressures up to 1.0 GPa loads up to 10kN, and displacements of up to 25 mm are possible. The oil based apparatus is operated at temperatures up to 300°C room temperature while a gas (i.e. Ar) based apparatus is used at room temperature.

**Hydrostatic Extrusion Apparatus:** Hydrostatic extrusion (e.g. pressure-to-air, pressure-to-pressure) can be conducted at temperatures up to 300 C on manually operated equipment interfaced with a computer data acquisition package. Pressures up to 2.0 GPa are possible, with reduction ratios up to 6 to 1, while various diagnostics provide real time monitoring of extrusion pressure and ram displacement.

**Advanced Forging Simulation Rig:** A multi-actuator: MTS machine based on a 330 kip, four post frame, enables sub-scale forging simulations over industrially relevant strain rates. A 110 kip forging actuator is powered by five nitrogen accumulators enabling loading rates up to 120 inches/sec on large specimens. A 220 kip indexing actuator provides precise deformation sequences for either single, or multiple, deformation sequences. Date acquisition at rates sufficient for analysis is available. Testing with heated dies is possible.

**Advanced Metal Forming Rig:** A four post frame with separate control of punch actuator speed and blank hold down pressure enables determination of forming limit diagrams. Dynamic control of blank hold down pressure is possible, with maximum punch actuator speeds of 11.8 inches/sec. A variety of die sets are available.

The remainder of the equipment in the AMMRC is summarized below:

**Servo-hydraulic Machines:** Four MTS Model 810 computer-controlled machines with load capacities of 3 kip, 20 kip, 50 kip, and 50 kip, permit tension, compression, and fatigue studies to be conducted under load-, strain-, or stroke control. Fatigue crack growth may be monitored via a dc potential drop technique as well as via KRAK gages applied to the specimen surfaces. Fatigue studies may be conducted at frequencies up to 30 Hz. In addition, an Instron Model 1331 20 kip Servo-hydraulic machine are available for both quasi-state and cyclic testing.

**Universal Testing Machines:** Three INSTRON screw-driven machines, including two INSTRON Model 1125 units permit tension, compression and torsion testing.

**Electromechanical Testing Machine:** A computer-controlled INSTRON Model 1361 can be operated under load-, strain-, or stroke control. Stroke rates as slow as 1 micrometer/hour are possible.

**Fatigue Testing Machines:** Three Sonntag fatigue machines and two R. R. Moore rotating-bending fatigue machines are available for producing fatigue-life (S-N) data. The Sonntag machines may be operated at frequencies up to 60 Hz.

**Creep Testing Machines:** Three constant load frames with temperature capabilities up to 800 C permit creep testing, while recently modified creep frames permit thermal cycling experiments as well as slow cyclic creep experiments.

**Impact Testing Machines:** Two Charpy impact machines with capacities ranging from 20 ft-lbs to 240 ft-lbs are available. Accessories include a Dynatup instrumentation package interfaced with an IBM PC, which enables recording of load vs. time traces on bend specimens as well as on tension specimens tested under impact conditions.

**Instrumented Microhardness Tester:** A Nikon Model QM High-Temperature Microhardness Tester permits indentation studies on specimens tested
at temperatures ranging from -196°C to 1600°C under vacuum and inert gas atmospheres. This unit is complemented by a Zwick Model 3212 Microhardness Tester as well as a variety of Rockwell Hardness and Brinell Hardness Testing Machines.

**The Swagelok Center for Surface Analysis of Materials (SCSAM)**

The Swagelok Center for Surface Analysis of Materials (SCSAM) is a multi-user facility providing cutting-edge major instrumentation for microcharacterization of materials. SCSAM’s instruments encompass a wide and complementary range of characterization techniques, which provide a comprehensive resource for high-resolution imaging, diffractometry, and spatially-resolved compositional analysis.

Current capabilities for SEM (scanning electron microscopy) include four scanning electron microscopes, three of which are equipped for FIB (focused ion beam) micromachining, XEDS (X-ray energy-dispersive spectrometry), and acquisition of EBSP (electron backscattering patterns). SCSAM operates a 300 kV high-resolution transmission electron microscope, equipped with field-emission gun and imaging energy filter. This instrument is capable of XEDS and EELS (electron energy-loss spectrometry). SCSAM’s SPM (scanning probe microscopy) capabilities include a UHV (ultra-high vacuum) variable-temperature atomic-resolution system for STM (scanning tunneling microscopy), STS (scanning tunneling spectroscopy), and all models of AFM (atomic-force microscopy), as well as a standard instrument for AFM, which can optionally be operated with a scanning n Liveindenter. A stand-alone automated nanoindenter is available as well. SCSAM also operates a laser scanning confocal optical microscope, dedicated to imaging inorganic materials and capable of performing Raman microscopy. For XRD (X-ray diffractometry), SCSAM provides 3 diffractometers capable of a variety of techniques. SCSAM’s surface analysis suite of instruments includes an instrument for ToF-SIMS (time-of-flight secondary-ion mass spectrometry), a SAM (scanning Auger microprobe) for spatially resolved AES (Auger electron spectrometry), and an instrument for XPS (X-ray photoelectron spectrometry, also known as ESCA, electron spectrometry for chemical analysis), that accomplishes high spatial resolution by operating with a focused X-ray beam.

SCSAM is administered directly by the CSE (Case School of Engineering) and is central to much of the research carried out by CSE’s seven departments. However, the facility is also extensively used by the CAS (College of Arts and Sciences) Departments of Physics, Chemistry, Biology, and Earth, Environmental, and Planetary Sciences, as well as many departments within the School of Medicine and the School of Dental Medicine. In addition to CWRU clients, many external institutions utilize SCSAM’s facilities, including NASA Glenn Research Center, the Cleveland Clinic, and numerous Ohio universities. More than 250 users utilize the facility in any given year.

SCSAM’s instruments are housed in a centralized area, allowing users convenient access to state-of-the-art tools for their research.

**Transmission Electron Microscopy Laboratory**

A transmission electron microscope is available that provides virtually all conventional and advanced microscopy techniques required for state-of-the-art materials research and involves an installed capacity worth $2,500,000.

The FEI Tecnai F30 300 kV field-emission gun energy-filtering high-resolution analytical scanning transmission electron microscope has a point resolution below 0.20 nm and an information resolution limit of 0.14 nm. The instrument is equipped with an EDAX system with a high-energy resolution Si-Li detector for XEDS (X-ray energy-dispersive spectrometry), a HAADF (high-angle annular dark-field) detector for STEM (scanning transmission electron microscopy), and a Gatan GIF 2002 imaging energy filter including a 2 k×2 k pixel slow-scan CCD camera. The GIF in conjunction with the field-emission gun enable EELS (electron energy-loss spectrometry) with an energy resolution down to below 1 eV. Further, the instrument is equipped with a NanoMegas TopSpin system for grain-orientation mapping and related techniques.

Conventional TEM techniques, such as bright-field and dark-field imaging, electron diffraction, or weak-beam dark-field imaging are used routinely to analyze line defects (dislocations) and planar defects (interfaces, grain boundaries, stacking faults) in crystalline materials. Advanced TEM techniques include the following:

- High-resolution TEM. This technique enables imaging the projected atomistic structure of extended crystal defects, such as heterophase interfaces, grain boundaries, or dislocations.
- CBED (convergent-beam electron diffraction). This technique can be used to obtain crystallographic information (space group) and to determine orientation relationships between small (even nanoscopic) crystallites.
- EFTEM (energy-filtering TEM). This denotes a suite of techniques enabled by an imaging energy filter. In particular, the techniques include zero (energy)-loss filtering for improved contrast in images and diffraction patterns and ESI (electron spectroscopic imaging), a technique that enables rapid elemental mapping with high spatial resolution based on element-characteristic energy losses of the primary electrons in the specimen. Specimen preparation facilities for TEM, in addition to the FIB systems described above, consist of two dimple-grinders, two electropolishing units, two state-of-the-art PIPS (precision ion polishing systems) by Gatan, and a Fischione NanoMill 1040 for highest-quality specimens by post-processing of FIB-prepared foils.

**Scanning Electron Microscopy Laboratory**

SEM (scanning electron microscopy) provides valuable specimen information by enabling imaging with particularly great depth of field and stereo-imaging with resolutions down to the nanometer range. The topography of nearly any solid surface is possible with SEM. Spectrochemical studies are enabled by XEDS (X-ray energy-dispersive spectrometry) systems capable of detecting elements from boron to uranium. The laboratory houses the following instruments:

- The xT Nova Nanolab 200 (FEI), a dual-beam system providing a FIB (focused ion beam) and a scanning electron beam. The focused ion beam is used for preparing thin foils suitable for TEM directly out of the specimen surface. At the same time, enabled by the scanning electron beam, this instrument includes a complete and very-high-quality scanning electron microscope. This construction has the advantage that the specimen can be observed by (high-resolution) SEM while being milled by the ion beam. Moreover, the Nova includes an internal “lift-out-” system for transferring the thin film generated by ion-beam milling onto a special Cu support grid, which can then be loaded into the specimen holder of a TEM. For elemental and crystallographic analysis, the system is equipped with a state-of-the-art Oxford Aztec system with a X-max 50mm² detector and a NORDLYS EBSP camera. EBSD mapping of phase and orientation
relies on evaluating EBSP patterns of every scan point and can be run on bulk materials and in transmission mode on TEM samples.

- The FEI Quanta 200 3D. This is a versatile low-vacuum SEM/FIB for 2D and 3D material characterization and analysis. It features three imaging modes: high-vacuum, low-vacuum, and ESEM, and can accommodate a wide range of samples. The instrument is equipped with a field-emission Ga ion source and a thermal electron emitter. The enabling technologies, integrated onto a single platform, further include high-volume milling capabilities, an ESEM differential-pumping variable-pressure vacuum system (oil-free), gaseous secondary and backscattered electron detectors for imaging and analysis in a gaseous chamber environment, a high-precision specimen goniometer with 50 mm travel along the x- and y-axis, and automation serving unattended sectioning with full access to e-beam, i-beam, and patterning.

- A Helios NanoLab™ 650, features FEI’s most recent advances in field-emission SEM and FIB (focused ion beam) technologies and their combined use. It is designed to access a “new world” of extremely high-resolution 2D and 3D characterization, 3D nanoprototyping, and higher quality TEM sample preparation. The Helios’s capability of robust and precise FIB slicing, combined with a high-precision piezo stage (150 x 150 mm²), superb SEM performance, and advanced software allow unattended sample preparation or 3D characterization and analysis. The outstanding imaging capabilities of the Helios NanoLab begin with its Elstar™ FESEM. Thanks to its integrated monochromator (UC) and beam deceleration, it delivers sub-nanometer resolution across the whole 1-30 kV range. The Elstar features other unique technologies such as constant power lenses for higher thermal stability and electrostatic scanning for higher deflection linearity and speed. Its through-the-lens detector, set for highest collection efficiency of SE (secondary electrons) and on-axis BSE (backscattered electrons), is complemented by FEI’s advanced detection suite including three novel detectors: two multi-segment solid state detectors: CBS retractable detector for backscattered electron imaging able to detect low kV BSE, a scanning transmission electron mode retractable detector able to record simultaneously BF, DF and HAADF images, and a third dedicated to FIB-SE and -SI (secondary ion) imaging. The Helios system is equipped with a state-of-the-art XEDS X-Max 80 mm² silicon drift detector (SDD) system by Oxford with an energy resolution of 125 eV at Mn Ka (5.899 keV) at full width at half maximum. The extremely large active area significantly increases the collection solid angle. This results in a detector that performs measurements either more quickly at conditions at which traditional systems would be used or at higher energy resolution. The increased sensitivity allows the system to operate at much lower beam currents. This reduces the risk of sample damage.

**Surface Science Laboratories**

SCSAM’s tools for surface science include three instruments for surface analysis in UHV (ultra-high vacuum), two scanning probe systems, and a dedicated nanoindenter, all detailed below:

- A PHI 680 scanning Auger microprobe. This system consists of a field-emission scanning electron microscope with a Schottky emission cathode, a secondary electron detector, and an axial cylindrical mirror analyzer with a multi-channel detector to collect Auger electrons produced during electron imaging. Very small spot sizes can be realized with this instrument, down to 7 nm. This is useful for high-resolution imaging and for Auger data acquisition using low beam currents. Inert gas sputtering (using a PHI 06-350 ion gun) is used to clean surface contamination from samples and to remove material from a small area on the surface for depth profiling. Several modes of operation are available to the user, including survey, line, profile, and elemental mapping. Capable of multi-point analysis, the instrument is a powerful tool for routine failure analysis and quality control of inorganic samples. An additional device permits in situ fracture of samples, at liquid nitrogen temperature if necessary.

- A PHI VersaProbe XPS Microprobe. Based on XPS (X-ray photoelectron spectrometry, also known as ESCA – electron spectrometry for chemical analysis), this is a multi-technique surface analysis instrument based on PHI’s highly developed scanning X-ray microprobe technology. The most important advantage of this instrument is that the VersaProbe can produce a focused, highly monochromatic X-ray beam that can be scanned over the specimen surface. In this instrument, a point source of X-rays is created by focusing an electron beam onto an Al anode. A monochromator, consisting of an ellipsoid-shaped crystal, collects X-rays from the point source and focuses them on the surface of the specimen. The focused X-ray beam can be scanned across the specimen surface by correspondingly scanning the electron beam across the surface of the aluminum anode. A major advantage of this design is that most of the photoelectrons generated by the focused X-ray beam are actually collected by the electron energy analyzer, whereas in the conventional design, most of the photoelectrons are lost. With the VersaProbe, the spot size can be varied between less than 10 μm diameter (for highest spatial resolution) to 100 μm (for highest sensitivity).

- A TRIFT V nanoTOF made by PHI. This is a time-of-flight secondary-ion mass spectrometer. This instrument is from the latest generation of PHI’s surface analysis line of ToF-SIMS instruments, utilizing a newly developed, high-quality "TRIFT" analyzer. It is equipped with an Au-, a C60-, and an Ar gun. An innovative new sample handling platform enables analysis of samples with complex geometries. In addition, the system has state-of-the-art charge compensation and ion gun performance.

ToF-SIMS (time-of-flight secondary-ion mass spectrometry) provides sub-micrometer 3D (!) elemental mapping. It can also be used to image the topography of solid surfaces. Different from D-SIMS (“dynamic” SIMS), ToF-SIMS enables analyzing the outermost one or two mono-layers of a sample while basically preserving molecular integrity. While D-SIMS provides primarily elemental information, ToF-SIMS surface analysis yields chemical and molecular information. ToF-SIMS is ideal for both organic and inorganic materials and can be used to characterize both insulating and conductive samples. With detection limits in the ppm to ppb range, shallow depth profiling capabilities and automated analysis, the nanoTOF can be used to study surface contamination, trace impurities, films, delamination failures etc. It is also a valuable tool to investigate surface modification chemistry and catalyst surface composition.

- A Dimension 3100 (Veeco Digital Instruments). This is a state-of-the-art multi-mode scanning probe microscope (SPM), equipped with a NanoScope IIIa controller and Quadrex signal processor for 16-bit resolution on all 3 axes. The tool works under atmospheric pressure at room temperature and can work in air and in liquids, so that a full range of materials (metals, insulators, ceramics, polymers, and biological specimens) can be investigated with minimal sample preparation. It can accept samples up to 20 cm in diameter, with a height limitation of < 1.5 cm and a surface roughness limitation of < 5.5 mm. The instrument is equipped with an in-line optical zoom.
microscope with color CCD camera, with a maximum magnification of 800X for precise placement of the SPM probe onto the sample. The Dimension 3100 can operate in numerous imaging modes, the primary operation being atomic force microscopy (AFM) in contact mode, tapping mode, and phase imaging mode. Other data collection techniques include conductive-AFM to characterize conductivity variations, magnetic force microscopy, which uses a ferromagnetic-coated tip to probe magnetic fields, and force-distance measurements, which are performed to study attractive and repulsive forces on a tip as it approaches and retracts from the sample surface. Further, the Dimension 3100 SPM has been upgraded by a “TriboScope,” an attachment for nanomechanical testing, made by Hysitron. The TriboScope is a quantitative, depth-sensing nanoindentation and nanoscratch system that interfaces with the SPM. This attachment enables quantitative characterization of mechanical properties (hardness, scratch resistance, wear resistance) on the nanometer length scale and in situ AFM imaging of the surface topography before and after mechanical testing. The capability of in situ imaging allows the user to choose the exact area, with sub-nm precision, for each nanoindentation/nanoscratch investigation, and to fully identify the local specimen surface.

- An RKH 7500 UHV VT. This system includes a variable-temperature ultra-high vacuum scanning probe microscope, made by RHK Technologies. This instrument is part of a complete UHV (ultra-high vacuum) system, which includes a separately pumped specimen preparation chamber and a load-lock chamber in addition to the actual SPM (scanning probe microscopy) chamber. The base pressure of the system is specified to $2.10^{-12}$ Pa. In the preparation chamber, an electron gun combined with a hemispherical electron energy analyzer is attached to enable chemical analysis of the specimen surface via AES (Auger electron spectroscopy). A specimen manipulator installed on the vertical axis of the chamber allows precise positioning of the specimen in front of the electron energy analyzer. The manipulator can be connected to a cryostat via a differentially-pumped rotary stage, permitting cooling the specimen down to 25 K. By resistive or electron-beam heating, it will also be possible to heat the specimen up to temperatures of 1500 K.

To be able to clean the specimen surface, the system includes an Ar sputter gun. Evaporators installed at ports in the lower half of the chamber enable the deposition of metals onto the specimen surface. A gas dosing system facilitates gas adsorption experiments without backfilling the entire chamber or opening the main chamber to change gases. A mass spectrometer constantly detects and analyzes residual gas in the chamber. Finally, the preparation chamber includes a port large enough for a retractable reverse view LEED (low-energy electron diffraction) system for studying the surface structure of the specimen.

Using a magnetic transfer arm, the specimen can be moved from the preparation chamber into the actual SPM chamber. This chamber houses a cantilever atomic force microscope combined with a scanning tunneling microscope, suitable to image the surface structure of conducting as well as non-conducting materials. Both instruments are capable of atomic-resolution imaging. The scanning tunneling microscope also permits probing the local work function and the local density of states in the specimen surface by STS (scanning tunneling spectrometry). All modes of SPM will work over a very broad range of specimen temperatures: 25 to 750 K. The SPM chamber accepts thermal evaporators, a sputter gun and a gas dosing system that can perform their functions while the sample is actively being studied by any of the available scanning probe techniques.

- An Agilent Nano Indenter G200. This is a very accurate, flexible, user-friendly instrument for nanomechanical testing. Electromagnetic actuation allows unparalleled dynamic range in force and displacement and measurement of deformation over six orders of magnitude (from nanometers to millimeters). Potential applications include a wide scope of materials, e.g. semiconductors, films, MEMs (wafer applications), coatings and DLC films, composite materials, fibers, polymers, metals, ceramics, and biomaterials.

**X-Ray Diffractometry Laboratory**

The XRD (X-ray diffractometry) laboratory contains equipment for studying the atomic structures of mainly crystalline inorganic materials. Three instruments are available:

- A Scintag X1 diffractometer system. This includes a theta/theta wide-angle goniometer, a 4.0 kW X-ray generator with Cu tube, a third axis stress attachment, a thermoelectrically cooled Peltier Ge detector, a film analysis system, a dedicated PC for data acquisition, and a turbomolecular-pump evacuated furnace attachment permitting sample temperatures up to 1700 K.

- A Bruker Discover D8 X-ray diffractometer. This instrument has a monochromatized X-ray source (normally used with a Co-Kα X-ray tube), configured in point-focus mode. X-ray collimators are available for spot sizes from 200 μm to 800 μm, with 500 μm typical. The instrument includes a four-circle Huber goniometer equipped with an xyz stage and a laser video system to allow precision alignment of samples. Enabled by the small spot size of the incident X-ray beam and the precision alignment, small samples sizes can be evaluated and the instrument achieves much higher spatial resolution than conventional X-ray diffractometers. The 2D solid-state detector (VÁNTEC-500) allows a wide range of XRD techniques to be executed in short time. The detector has high sensitivity and is useful for detecting trace phases that might be missed by a conventional diffractometer. In addition, the detector allows rapid measurements of both stress and texture in a wide variety of materials. Software includes Diffrac.EVA for phase identification with the ICDD database and Diffrac.LEPTOS for stress measurement.

- The Rigaku D/MAX 2200 Powder X-ray Diffractometer is equipped with a horizontal goniometer, capable of performing typical $θ–2θ$ scans. The scanning speed can be varied from 0.002 °/min to 100 °/min. The divergence, scattering, and receiving slits are fully automated and controlled through a graphical user interface within the software. The D/MAX 2200 complements SCSAM’s two other XRD units as it is equipped with a Cr anode. The wavelength of Cr-Kα X-rays (0.229 nm) is suitable for steel alloys that exhibit heavy fluorescence with Cu-Kα X-rays (0.154 nm). In addition, the larger wavelength is preferred when trying to determine small changes in the lattice parameters, as peaks are shifted to higher 2θ values, which provide greater sensitivity to small changes in the lattice parameter. The sensitivity of the peak shift is ideal for measuring residual stress and determining solvus curves in binary phase diagrams.

**Electronic Properties Laboratory**

**Crystal Growth and Analysis Laboratory**

The Crystal Growth and Analysis Laboratory is equipped for research studies and characterization of bulk semiconductor and photonic materials. The growth facilities include a high pressure Czochralski
Magnetometry Laboratory
The Magnetometry Laboratory has facilities used to investigate the magnetic properties of materials. This laboratory has two instruments:

- A Lake Shore Cryotronics Model 7410 Vibrating Sample Magnetometer for measurement of hysteresis loops (at constant temperature) and thermomagnetic measurements (at constant magnetic field). The maximum applied field at room temperature (without furnace in place) is 3.1 Tesla. For high temperature measurements, the maximum applied field is 2.5 Tesla over the temperature range from room temperature to 1000°C.
- A home-built magnetostriction measurement system has been designed and built to measure the shape change of magnetic materials under applied magnetic fields. Better than 1 ppm sensitivity is possible by this strain gage technique. An applied field of ~0.2 Tesla is used to saturate samples.

Fuel Cell Testing Laboratory
Facilities (located in the A. W. Smith Building) for testing of solid oxide fuel cells include:

- 2 test stands for 4” cells and small stacks (Fuel Cell Technologies); test temperatures to 1000°C; professional turnkey LabView interface for system control and data acquisition
- 2 test stands for 1” cells; test temperatures to 1000°C; LabView interface for complete system control and data acquisition; Omega mass flow controllers; Keithley and Amrel electronics; AutoLab Electrochemical Analyzer for I-V, galvanostatic or amperometric testing and AC impedance spectroscopy
- All test stands contained in dedicated enclosures rated for use with hydrogen, hydrogen sulfide, and carbon monoxide with ventilation system, leak detection, tank pressure monitors, alarm system
- Dedicated furnaces and ovens for preparing cells for testing

SDLE Research Center
The SDLE Research Center was established in 2011 with funding from Ohio Third Frontier, and is dedicated to advancing the field of longevity and degradation science. The research center activities focus on durability and degradation of environmentally exposed, long lived materials and technologies such as photovoltaics (PV), energy efficient lighting, and building envelope applications. The Center develops real-time and accelerated protocols for exposure to solar radiation and related environmental stressors to enable the evaluation of the environmental durability and lifetime of materials, components, and products. Data scientists identify statistically significant relationships using a data analytics platform (Energy-CRADLE) developed in the center. Researchers perform post-exposure optical and thermo-mechanical measurements to develop quantitative mechanistic models of degradation processes. The SDLE Research Center’s capabilities and equipment include:

- Outdoor solar exposures: SunFarm with 14 dual-axis solar trackers with multi-sun concentrators, and power degradation monitoring
- Solar simulators for 1-1000X solar exposures
- Multi-factor environmental test chambers with temperature, humidity, freeze/thaw, and cycling
- A full suite of optical, interfacial, thermo-mechanical and electrical evaluation tools for materials, components and systems

The Wind Energy Research and Commercialization (WERC) Center
The WERC Center is a multidisciplinary center for use by students, faculty, and industry providing instrumentation for wind resource characterization and research platforms in operating wind turbines. The WERC Center was established in 2010 with funding from the Ohio Department of Development Third Frontier Wright Project and the Department of Energy. Additional support was provided by the following inaugural industrial partners: Cleveland Electric Laboratories, The Lubrizol Corporation, Parker Hannifin Corporation, Azure Energy LLC, Rockwell Automation, Inc., Swiger Coil Systems LLC, and Wm. Sopko & Sons Co.

The instruments in the WERC Center include:

- A continuous scan ZephIR LiDAR, manufactured by Natural Power. This instrument measures horizontal and vertical wind velocity along with wind direction at 1 Hz frequency at five user set heights up to 200 m.
- Five meteorological measurement systems: 3 on campus; 1 with the off campus wind turbines; and one at the City of Cleveland’s water intake crib located 3.5 miles offshore in Lake Erie.
- An ice thickness sensor that is deployed at the bottom of Lake Erie each fall and retrieved in the spring.
- A NorthWind 100 wind turbine manufactured by Northern Power Systems in Barre, VT USA. This 100kW community scale wind turbine has a direct drive generator with full power inverters, stall control blades with a 21 m rotor diameter, and a 37 m hub height. This wind turbine is located on campus just east of Van Horn field and began operation in November, 2010.
- A Vestas V-27 wind turbine originally manufactured by Vestas in Denmark. This 225kW medium scale wind turbine has a gearbox drive generator, pitch controlled blades with a 27 m rotor diameter, and a 30 m hub height. In addition it has a 50kW generator for low wind generation. This wind turbine is located at an industrial site in Euclid, OH about 15 minutes from campus and began operation in March, 2012.
- A Nordex N-54 wind turbine originally manufactured by Nordex in Germany. This 1.0MW utility scale wind turbine has a gearbox drive generator, stall control blades with a 54 m rotor diameter, and a 70 m hub height. In addition it has a 200kW generator for low wind generation. This wind turbine is located at an industrial site in Euclid, OH about 15 minutes from campus and began operation in October, 2012.

EMSE 110. Transitioning Ideas to Reality I - Materials in Service of Industry and Society, 1 Unit.
In order for ideas to impact the lives of individuals and society they must be moved from “blue sky” to that which is manufacturable. Therein lies true creativity - design under constraint. Greater Cleveland is fortunate to have a diverse set of industries that serve medical, aerospace, electric, and advanced-materials technologies. This course involves trips to an array of work sites of leading companies to witness first-hand the processes and products, and to interact directly with practitioners. Occasional in-class speakers with demonstrations will be used when it is not logistically reasonable to visit off-site.
EMSE 120. Transitioning Ideas to Reality II - Manufacturing Laboratory. 2 Units.
This course complements EMSE 110. In that class students witness a diverse array of processing on-site in industry. In this class students work in teams and as individuals within processing laboratories working with an array of “real materials” to explore the potential of casting, machining, and deformation processes to produce real parts and/or components. An introduction to CAD as a means of communication is provided. The bulk of the term is spent in labs doing hands-on work. Planned work is carried out to demonstrate techniques and potential. Students have the opportunity to work independently or in teams to produce articles as varied as jewelry, electronics, transportation vehicles, or novel components or devices of the students’ choosing.

EMSE 125. Freshman Research in Materials Science and Engineering. 1 Unit.
Freshman students conduct independent research in the area of material science and engineering, working closely with graduate student(s) and/or postdoctoral fellow(s), and supervised by an EMSE faculty member. An average of 5-6 hr/wk in the laboratory, periodic updates, and an end of semester report is required. Prereq: Limited to freshman, with permission of instructor.

EMSE 220. Materials Laboratory I. 2 Units.

EMSE 228. Mathematical Methods for Materials Science and Engineering. 3 Units.
Problems in materials science and engineering drawn from thermodynamics, material property measurements, heat transfer, mass transfer, and failure analysis. Students will develop a fundamental understanding of the basis for solving these problems including understanding the constituent equations, solution methods, and analysis and presentation of results. Students will then solve these problems using current computational tools employed by practicing materials engineers and scientists. Advantages and disadvantages of techniques using spreadsheets, programming languages, and specialized programs. Recommended preparation or recommended co-requisite: MATH 224 or MATH 228. Prereq: EMSE 276 and (ENGR 131 or EEC 132) and (PHYS 121 or PHYS 123) and (MATH 122 or MATH 124).

EMSE 276. Materials Properties and Design. 3 Units.
Relation of crystal structure, microstructure, and chemical composition to the properties of materials. The role of materials processing in controlling structure so as to obtain desired properties, using examples from metals, ceramics, semiconductors, and polymers. Design content includes exercises in materials selection, and in design of materials to meet specified performance requirements. Prereq: MATH 121 and (ENGR 145 or EMSE 146). Prereq or Coreq: PHYS 122 or PHYS 124.

EMSE 307. Foundry Metallurgy. 3 Units.
Introduction to solid-liquid phase transformations and their application to foundry and metal casting processes. Includes application of nucleation and growth to microstructural development, application of thermodynamics to molten metal reactions, application of the principles of fluid flow and heat transfer to gating and riser design, and introduction to basic foundry and metal casting technology. Recommended preparation: EMSE 202 and EMSE 203 and ENGR 225.

EMSE 308. Welding Metallurgy. 3 Units.
Introduction to arc welding and metallurgy of welding. The course provides a broad overview of different industrial applications requiring welding, the variables controlling critical property requirements of the weld and a survey of the different types of arc welding processes. The course details the fundamental concepts that govern the different aspects of arc welding including the welding arc, weld pool solidification, precipitate formation and solid state phase transformations. Offered as EMSE 308 and EMSE 408. Coreq: EMSE 327.

EMSE 319. Processing and Manufacturing of Materials. 3 Units.
Introduction to processing technologies by which materials are manufactured into engineering components. Discussion of how processing methods are dependent on desired composition, structure, microstructure, and defects, and how processing affects material performance. Emphasis will be placed on processes and treatments to achieve or improve chemical, mechanical, physical performance and/or aesthetics, including: casting, welding, forging, cold-forming, powder processing of metals and ceramics, and polymer and composite processing. Coverage of statistics and computational tools relevant to materials manufacturing. Prereq: EMSE 276 or EMSE 201.

EMSE 320. Materials Laboratory II. 1 Unit.
Measurement of thermophysical properties of materials emphasizing thermal and electrical properties of materials. Laboratory teams are selected for all experiments. Statistical analysis of experimental results also emphasized. Recommended preparation or corequisite: EMSE 276.

EMSE 325. Undergraduate Research in Materials Science and Engineering. 1 - 3 Units.
Undergraduate laboratory research in materials science and engineering. Students will undertake an independent research project alongside graduate student(s) and/or postdoctoral fellow(s), and will be supervised by an EMSE faculty member. Written and oral reports will be given on a regular basis, and an end of semester report is required. The course can be repeated up to four (4) times for a total of six (6) credit hours. Prereq: Sophomore or Junior standing and consent of instructor.

EMSE 327. Thermodynamic Stability and Rate Processes. 3 Units.
An introduction to thermodynamics of materials as applied to metals, ceramics, polymers and optical/radiant heat transfer for photovoltaics. The laws of thermodynamics are introduced and the general approaches used in the thermodynamic method are presented. Systems studied span phase stability and oxidation in metals and oxides; nitride ceramics and semiconductors; polymerization, crystallization and block copolymer domain formation; and the thermodynamics of systems such as for solar power collection and conversion. Recommended preparation: EMSE 228 and ENGR 225 or equivalent. Prereq: EMSE 276 or EMSE 201.

EMSE 328. Meso-scale Science Including Nanotechnology. 3 Units.
Mesoscale science focuses on addressing the frontiers of complex systems, between quantum and classical, nano and macro, and across the four dimensions of space and time. Nanoscience continues to advance, and multi-scale approaches are used to bridge orders of magnitude in length scales. This course will explore tools that are needed to bridge different length scales, including crystallography (crystal symmetries, point groups, crystal systems and space groups), crystal chemistry, characterization of microstructures (including grains, inclusions, second phases, texture, and voids), diffraction principles and their application in characterizing materials at differing length scales (nano, micro, meso, macro), device characterization methods, and fabrication technologies and processes. Offered as: EMSE 328 and EMSE 428. Prereq: (MATH 223 or MATH 227) and (EMSE 276 or EMSE 201).
EMSE 330. Materials Laboratory III. 2 Units.

EMSE 335. Strategic Metals and Materials for the 21st Century. 3 Units.
This course seeks to create an understanding of the role of mineral-based materials in the modern economy focusing on how such knowledge can and should be used in making strategic choices in an engineering context. The history of the role of materials in emerging technologies from a historical perspective will be briefly explored. The current literature will be used to demonstrate the connectedness of materials availability and the development and sustainability of engineering advances with examples of applications exploiting structural, electronic, optical, magnetic, and energy conversion properties. Processing will be comprehensively reviewed from source through refinement through processing including property development through application of an illustrative set of engineering materials representing commodities, less common metals, and minor metals. The concept of strategic recycling, including design for recycling and waste stream management will be considered. Offered as EMSE 335 and EMSE 435. Prereq: Senior standing or graduate student.

EMSE 343. Materials for Electronics and Photonics. 3 Units.
This course covers the basics of planar processing, which is the foundation of producing semiconductor chips and photonic devices, and the way these devices are incorporated into electronics and display technologies. Basic characteristics of semiconductors and optoelectronic devices; and how advances in these technologies arise from, and drive, advances in materials and device architecture. Offered as: EMSE 343 and EMSE 443. Prereq: (PHYS 122 or PHYS 124) and (EMSE 276 or EMSE 201).

EMSE 345. Materials for Biological and Medical Technology. 3 Units.
A survey of natural biomaterials and synthetic biomedical materials from the perspective of materials science and engineering, focusing on how processing/synthesis, structure, and properties determine materials performance. Structure and properties of bones and teeth, soft tissue, and cartilage. Introduction to properties and applications of materials for medical technologies, such as orthopedic implants, sensors, transducers, and materials for biomedical imaging and drug delivery. Selected case studies. Biomimetics as a design strategy for synthetic materials. Prereq: ENGR 200 and (ENGR 145 or EMSE 146).

EMSE 349. Materials for Energy and Sustainability. 3 Units.
Levels and categories of energy usage in the U.S. and the world. Availability of raw materials, including strategic materials; factors affecting global reserves and annual world production. Design strategies, and how the inclusion of environmental impacts as design criteria can alter materials selections. Resource demand (energy and water) of materials production, fabrication, and recycling. Roles of engineered materials in renewable or advanced energy technologies: photovoltaics, fuel cells, wind, batteries, capacitors, thermoelectrics. Energy harvesting. Role of magnetic materials in energy technology. Materials in energy-efficient lighting. Energy return on energy invested. Semester projects will enable students to explore related topics (e.g. geothermal; biomass; solar thermal; advances in energy-efficient manufacturing) in greater depth. Offered as EMSE 349 and EMSE 449. Prereq: ENGR 225 and (ENGR 145 or EMSE 146) and (PHYS 122 or PHYS 124) or requisites not met permission.

EMSE 356. Surface Engineering of Materials. 3 Units.
Introduction to surface engineering of materials, understood as a treatment that allows the surface to perform functions different from those performed by the bulk. This may include engineering the mechanical, chemical, electrical, magnetic, or optical properties of the surface and near-surface regions for specific applications. For a variety of technologically important classes of materials, the course reviews general concepts of surface engineering, the underlying physical and materials science principles, technical implementations, and typical applications. Recommended for graduate students and advanced undergraduate students. Offered as EMSE 365 and EMSE 465. Prereq: (EMSE 276 and ENGR 225) or Requisites Not Met permission.

EMSE 372. Structural Materials by Design. 4 Units.

EMSE 379. Design for Lifetime Performance. 3 Units.

EMSE 396. Special Project or Thesis. 1 - 18 Units.
Special research projects or undergraduate thesis in selected material areas.

EMSE 398. Senior Project in Materials I. 1 Unit.
Independent Research project. Projects selected from those suggested by faculty; usually entail original research. The EMSE 398 and 399 sequence form an approved SAGES capstone. Counts as SAGES Senior Capstone.

EMSE 399. Senior Project in Materials II. 2 Units.
Independent Research project. Projects selected from those suggested by faculty; usually entail original research. Requirements include periodic reporting of progress, plus a final oral presentation and written report. Counts as SAGES Senior Capstone. Prereq: EMSE 398.
EMSE 400T. Graduate Teaching I. 0 Unit.
To provide teaching experience for all Ph.D.-bound graduate students. This will include preparing exams/ quizzes, homework, leading recitation sessions, tutoring, providing laboratory assistance, and developing teaching aids that include both web-based and classroom materials. Graduate students will meet with supervising faculty member throughout the semester. Grading is pass/fail. Students must receive three passing grades and up to two assignments may be taken concurrently. Recommended preparation: Ph.D. student in Materials Science and Engineering.

EMSE 405. Dielectric and Electrical Properties of Materials. 3 Units.

EMSE 408. Welding Metallurgy. 3 Units.
Introduction to arc welding and metallurgy of welding. The course provides a broad overview of different industrial applications requiring welding, the variables controlling critical property requirements of the weld and a survey of the different types of arc welding processes. The course details the fundamental concepts that govern the different aspects of arc welding including the welding arc, weld pool solidification, precipitate formation and solid state phase transformations. Offered as EMSE 308 and EMSE 408.

EMSE 409. Deformation Processing. 3 Units.
Flow stress as a function of material and processing parameters; yielding criteria; stress states in elastic-plastic deformation; forming methods: forging, rolling, extrusion, drawing, stretch forming, composite forming. Recommended preparation: EMSE 303.

EMSE 413. Fundamentals of Materials Engineering and Science. 3 Units.
Provides a background in materials for graduate students with undergraduate majors in other branches of engineering and science: reviews basic bonding relations, structure, and defects in crystals. Lattice dynamics; thermodynamic relations in multi-component systems; microstructural control in metals and ceramics; mechanical and chemical properties of materials as affected by structure; control of properties by techniques involving structure property relations; basic electrical, magnetic and optical properties.

EMSE 417. Properties of Materials in Extreme Environments. 3 Units.
Fundamentals of degradation pathways of materials under extreme conditions; thermodynamic stability of microstructures, deformation mechanisms, and failure mechanisms. Extreme conditions that will typically be addressed include: elevated temperatures, high-strain rates (ballistic), environmental effects, nuclear radiation, and small scales. Examples will be drawn from recent events as appropriate.

EMSE 421. Fracture of Materials. 3 Units.

EMSE 422. Failure Analysis. 3 Units.
Methods and procedures for determining the basic causes of failures in structures and components. Recognition of fractures and excessive deformations in terms of their nature and origin. Development and full characterization of fractures. Review of essential mechanical behavior concepts and fracture mechanics concepts applied to failure analyses in inorganic, organic, and composite systems. Legal, ethical, and professional aspects of failures from service. Prereq: EMSE 372 or EMAE 372 or Requisites Not Met permission.

EMSE 427. Dislocations in Solids. 3 Units.
Elasticity and dislocation theory; dislocation slip systems; kinks and dislocation motion; jobs and dislocation interactions, dislocation dissociation and stacking faults; dislocation multiplication, applications to yield phenomena, work hardening and other mechanical properties.

EMSE 428. Meso-scale Science Including Nanotechnology. 3 Units.
Mesoscale science focuses on addressing the frontiers of complex systems, between quantum and classical, nano and macro, and across the four dimensions of space and time. Nanoscience continues to advance, and multi-scale approaches are used to bridge orders of magnitude in length scales. This course will explore tools that are needed to bridge different length scales, including crystallography (crystal symmetries, point groups, crystal systems and space groups), crystal chemistry, characterization of microstructures (including grains, inclusions, second phases, texture, and voids), diffraction principles and their application in characterizing materials at differing length scales (nano, micro, meso, macro), device characterization methods, and fabrication technologies and processes. Offered as: EMSE 328 and EMSE 428. Prereq: (MATH 223 or MATH 227) and (EMSE 276 or EMSE 201).

EMSE 430. Additive Manufacturing of Metals, Polymers, and Ceramics. 3 Units.
Additive manufacturing, though rooted in well-established unit operations, has emerged as a distinctive approach to the production of components and assemblies. This course will cover the conceptual approach, its history, the current state of the art, and analysis of projections of it future role. The respective advances in digital description of parts and digital control of processes will be described as machine design and construction. The emphasis, however, will be on the processing-structure-property relationships. Polymers, metals, and ceramics will be treated separately and contrasted. The course will make extensive use of current literature. Prereq: EMSE 276 or Requisites Not Met permission.
EMSE 435. Strategic Metals and Materials for the 21st Century. 3 Units.
This course seeks to create an understanding of the role of mineral-based materials in the modern economy focusing on how such knowledge can and should be used in making strategic choices in an engineering context. The history of the role of materials in emerging technologies from a historical perspective will be briefly explored. The current literature will be used to demonstrate the connectedness of materials availability and the development and sustainability of engineering advances with examples of applications exploiting structural, electronic, optical, magnetic, and energy conversion properties. Processing will be comprehensively reviewed from source through refinement through processing including property development through application of an illustrative set of engineering materials representing commodities, less common metals, and minor metals. The concept of strategic recycling, including design for recycling and waste stream management will be considered. Offered as EMSE 335 and EMSE 435. Prereq: Senior standing or graduate student.

EMSE 443. Materials for Electronics and Photonics. 3 Units.
This course covers the basics of planar processing, which is the foundation of producing semiconductor chips and photonic devices, and the way these devices are incorporated into electronics and display technologies. Basic characteristics of semiconductors and optoelectronic devices; and how advances in these technologies arise from, and drive, advances in materials and device architecture. Offered as: EMSE 343 and EMSE 443. Prereq: (PHYS 122 or PHYS 124) and (EMSE 276 or EMSE 201).

EMSE 449. Materials for Energy and Sustainability. 3 Units.
Levels and categories of energy usage in the U.S. and the world. Availability of raw materials, including strategic materials; factors affecting global reserves and annual world production. Design strategies, and how the inclusion of environmental impacts as design criteria can alter materials selections. Resource demand (energy and water) of materials production, fabrication, and recycling. Roles of engineered materials in renewable or advanced energy technologies: photovoltaics, fuel cells, wind, batteries, capacitors, thermoelectrics. Energy harvesting. Role of magnetic materials in energy technology. Materials in energy-efficient lighting. Energy return on energy invested. Semester projects will enable students to explore related topics (e.g. geothermal; biomass; solar thermal; advances in energy-efficient manufacturing) in greater depth. Offered as EMSE 349 and EMSE 449. Prereq: ENGR 225 and (ENGR 145 or EMSE 146) and (PHYS 122 or PHYS 124) or requisites not met permission.

EMSE 463. Magnetism and Magnetic Materials. 3 Units.
This course covers the fundamentals of magnetism and application of modern magnetic materials especially for energy and data storage technologies. The course will focus on intrinsic and extrinsic magnetic properties, processing of magnetic materials to achieve important magnetic performance metrics, and the state-of-the-art magnetic materials used today. The topics related to intrinsic properties, include: magnetic dipole moments, magnetization, exchange coupling, magnetic anisotropy and magnetostriction. Topics related to extrinsic properties, include: magnetic hysteresis, frequency dependent magnetic response and magnetic losses. Technologically important permanent magnets (including rare earth containing alloys and magnetic oxides), soft magnets (including electrical steels, amorphous, ferrites, and nanocrystalline alloys), and thin film materials (including iron platinum) will be discussed in the context of their technological interest. Throughout the course, experimental techniques and data analysis will be discussed. The course is suitable for most graduate students and advanced undergraduates in engineering and science.

EMSE 465. Surface Engineering of Materials. 3 Units.
Introduction to surface engineering of materials, understood as a treatment that allows the surface to perform functions different from those performed by the bulk. This may include engineering the mechanical, chemical, electrical, magnetic, or optical properties of the surface and near-surface regions for specific applications. For a variety of technologically important classes of materials, the course reviews general concepts of surface engineering, the underlying physical and materials science principles, technical implementations, and typical applications. Recommended for graduate students and advanced undergraduate students. Offered as EMSE 365 and EMSE 465.

EMSE 499. Materials Science and Engineering Colloquium. 0 - 1 Units.
Invited speakers deliver lectures on topics of active research in materials science. Speakers include researchers at universities, government laboratories, and industry. Course is offered both of 1 credit and 0 credits. Attendance is required for both, and graded coursework in the form of a term paper is required when registering for 1 credit. Offered as EMSE 499 and EMSE 599.

EMSE 500T. Graduate Teaching II. 0 Unit.
To provide teaching experience for all Ph.D.-bound graduate students. This will include preparing exams/quizzes/homework, leading recitation sessions, tutoring, providing laboratory assistance, and developing teaching aids that include both web-based and classroom materials. Graduate students will meet with supervising faculty member throughout the semester. Grading is pass/fail. Students must receive three passing grades and up to two assignments may be taken concurrently. Recommended preparation: Ph.D. student in Materials Science and Engineering.

EMSE 503. Structure of Materials. 3 Units.
The structure of materials and physical properties are explored in terms of atomic bonding and the resulting crystallography. The course will cover basic crystal chemistry, basic crystallography (crystal symmetries, point groups, translation symmetries, space lattices, and crystal classes), basic characterization techniques and basic physical properties related to a materials structure.

EMSE 504. Thermodynamics of Solids. 3 Units.

EMSE 505. Phase Transformations, Kinetics, and Microstructure. 3 Units.
Phase diagrams are used in materials science and engineering to understand the interrelationships of composition, microstructure, and processing conditions. The microstructure and phases constitution of metallic and nonmetallic systems alike are determined by the thermodynamic driving forces and reaction pathways. In this course, solution thermodynamics, the energetics of surfaces and interfaces, and both diffusional and diffusionless phase transformations are reviewed. The development of the laws of diffusion and its application for both melts and solids are covered. Phase equilibria and microstructure in multicomponent systems will also be discussed.
EMSE 509. Conventional Transmission Electron Microscopy. 3 Units. 
Introduction to transmission electron microscopy-theoretical background and practical work. Lectures and laboratory experiments cover the technical construction and operation of transmission electron microscopes, specimen preparation, electron diffraction by crystals, electron diffraction techniques of TEM, conventional TEM imaging, and scanning TEM. Examples from various fields of materials research illustrate the application and significance of these techniques. Recommended preparation: Consent of instructor.

EMSE 512. Advanced Techniques of Transmission Electron Microscopy. 3 Units. 
Theory and laboratory experiments to learn advanced techniques of transmission electron microscopy, including high-resolution transmission electron microscopy (HRTEM), convergent-beam electron diffraction (CBED), microanalysis using X-ray energy-dispersive spectroscopy (XEDS) and electron energy-loss spectroscopy (EELS), and electron-spectroscopic imaging (ESI) for elemental mapping. Recommended preparation: EMSE 509.

EMSE 515. Analytical Methods in Materials Science. 3 Units. 
Microcharacterization techniques of materials science and engineering: SPM (scanning probe microscopy), SEM (scanning electron microscopy), FIB (focused ion beam) techniques, SIMS (secondary ion mass spectrometry), EPMA (electron probe microanalysis), XPS (X-ray photoelectron spectrometry), and AES (Auger electron spectrometry). ESCA (electron spectrometry for chemical analysis). The course includes theory, application examples, and laboratory demonstrations.

EMSE 599. Materials Science and Engineering Colloquium. 0 - 1 Units. 
Invited speakers deliver lectures on topics of active research in materials science. Speakers include researchers at universities, government laboratories, and industry. Course is offered both of 1 credit and 0 credits. Attendance is required for both, and graded coursework in the form of a term paper is required when registering for 1 credit. Offered as EMSE 499 and EMSE 599.

EMSE 600T. Graduate Teaching III. 0 Units. 
To provide teaching experience for all Ph.D.-bound graduate students. This will include preparing exam/quizzes/homework, leading recitation sessions, tutoring, providing laboratory assistance, and developing teaching aids that include both web-based and classroom materials. Graduate students will meet with supervising faculty member throughout the semester. Grading is pass/fail. Students must receive three passing grades and up to two assignments may be taken concurrently. Recommended preparation: Ph.D. student in Materials Science and Engineering.

EMSE 601. Independent Study. 1 - 18 Units.

EMSE 649. Special Projects. 1 - 18 Units.

EMSE 651. Thesis M.S.. 1 - 18 Units. 
Required for Master's degree. A research problem in metallurgy, ceramics, electronic materials, biomaterials or archeological and art historical materials, culminating in the writing of a thesis.

EMSE 701. Dissertation Ph.D.. 1 - 9 Units. 
Required for Ph.D. degree. A research problem in metallurgy, ceramics, electronic materials, biomaterials or archeological and art historical materials, culminating in the writing of a thesis. Prereq: Predoctoral research consent or advanced to Ph.D. candidacy milestone.

DSCI 134. Introduction to Applied Data Science. 3 Units. 
This course is an introduction to data science and analytics. In the first half of the course, students will develop a basic understanding of how to manipulate, analyze and visualize large data in a distributed computing environment, with an appreciation of open source development, security and privacy issues. In the second half of the course, students will gain experience in data manipulation and analysis using scripted programming languages such as Python.

DSCI 351. Exploratory Data Science. 3 Units. 
In this course, we will learn data science and analysis approaches to identify statistically significant relationships and better model and predict the behavior of these systems. We will assemble and explore real-world datasets, perform clustering and pair plot analyses to investigate correlations, and logistic regression will be employed to develop associated predictive models. Results will be interpreted, visualized and discussed. We will introduce basic elements of statistical analysis using R Project open source software for exploratory data analysis and model development. R is an open-source software project with broad abilities to access machine-readable open-data resources, data cleaning and munging functions, and a rich selection of statistical packages, used for data analytics, model development and prediction. This will include an introduction to R data types, reading and writing data, looping, plotting and regular expressions, so that one can start performing variable transformations for linear fitting and developing structural equation models, while exploring for statistically significant relationships. Offered as DSCI 351, DSCI 351M and DSCI 451. Prereq: (ENGR 131 or EECS 132 or DSCI 134) and (STAT 312R or STAT 201R or SYBB 310 or PQHS/EPBI 431).

DSCI 352. Applied Data Science Research. 3 Units. 
This is a project based data science research class, in which project teams identify a research project under the guidance of a domain expert professor. The research is structured as a data analysis project including the 6 steps of developing a reproducible data science project, including: 1: Define the ADS question, 2: Identify, locate, and/or generate the data 3: Exploratory data analysis 4: Statistical modeling and prediction 5: Synthesizing the results in the domain context 6: Creation of reproducible research, including code, datasets, documentation and reports. During the course special topic lectures will include Ethics, Privacy, Openness, Security, Ethics. Value. Offered as DSCI 352 and DSCI 452. Prereq: (DSCI 133 or DSCI 134 or ENGR 131 or EECS 132) and (STAT 312R or STAT 201R or SYBB 310 or PQHS/EPBI 431 or OPRE 207) and (DSCI 351 or (SYBB 311A and SYBB 311B and SYBB 311C and SYBB 311D) or SYBB 321 or MKMR 201).
DSCI 353. Data Science: Statistical Learning, Modeling and Prediction. 3 Units.
In this course, we will use an open data science tool chain to develop reproducible data analyses useful for inference, modeling and prediction of the behavior of complex systems. In addition to the standard data cleaning, assembly and exploratory data analysis steps essential to all data analyses, we will identify statistically significant relationships from datasets derived from population samples, and infer the reliability of these findings. We will use regression methods to model a number of both real-world and lab-based systems producing predictive models applicable in comparable populations. We will assemble and explore real-world datasets, use pair-wise plots to explore correlations, perform clustering, self-similarity, and logistic regression develop both fixed-effect and mixed-effect predictive models. We will introduce machine-learning approaches for classification and tree-based methods. Results will be interpreted, visualized and discussed. We will introduce the basic elements of data science and analytics using R Project open source software. R is an open-source software project with broad abilities to access machine-readable open-data resources, data cleaning and assembly functions, and a rich selection of statistical packages, used for data analytics, model development, prediction, inference and clustering. For students with little prior R experience, we’ll introduce resources to learn R data types, reading and writing data, looping, plotting and regular expressions. With this background, it becomes possible to start performing variable transformations for linear regression fitting and developing structural equation models, fixed-effects and mixed-effects models along with other statistical learning techniques, while exploring for statistically significant relationships. The class will be structured to have a balance of theory and practice. We’ll split class into Foundation and Practicum  a) Foundation: lectures, presentations, discussion b) Practicum: coding, demonstrations and hands-on data science work. Offered as DSCI 353, DSCI 353M and DSCI 453.

DSCI 451. Exploratory Data Science. 3 Units.
In this course, we will learn data science and analysis approaches to identify statistically significance relationships and better model and predict the behavior of these systems. We will assemble and explore real-world datasets, perform clustering and pair plot analyses to investigate correlations, and logistic regression will be employed to develop associated predictive models. Results will be interpreted, visualized and discussed. We will introduce basic elements of statistical analysis using R Project open source software for exploratory data analysis and model development. R is an open-source software project with broad abilities to access machine-readable open-data resources, data cleaning and munging functions, and a rich selection of statistical packages, used for data analytics, model development and prediction. This will include an introduction to R data types, reading and writing data, looping, plotting and regular expressions, so that one can start performing variable transformations for linear fitting and developing structural equation models, while exploring for statistically significant relationships. Offered as DSCI 351, DSCI 351M and DSCI 451.

DSCI 452. Applied Data Science Research. 3 Units.
This is a project based data science research class, in which project teams identify a research project under the guidance of a domain expert professor. The research is structured as a data analysis project including the 6 steps of developing a reproducible data science project, including 1: Define the ADS question, 2: Identify, locate, and/or generate the data 3: Exploratory data analysis 4: Statistical modeling and prediction 5: Synthesizing the results in the domain context 6: Creation of reproducible research, Including code, datasets, documentation and reports. During the course special topic lectures will include Ethics, Privacy, Openness, Security. Ethics. Value. Offered as DSCI 352 and DSCI 452.

DSCI 453. Data Science: Statistical Learning, Modeling and Prediction. 3 Units.
In this course, we will use an open data science tool chain to develop reproducible data analyses useful for inference, modeling and prediction of the behavior of complex systems. In addition to the standard data cleaning, assembly and exploratory data analysis steps essential to all data analyses, we will identify statistically significant relationships from datasets derived from population samples, and infer the reliability of these findings. We will use regression methods to model a number of both real-world and lab-based systems producing predictive models applicable in comparable populations. We will assemble and explore real-world datasets, use pair-wise plots to explore correlations, perform clustering, self-similarity, and logistic regression develop both fixed-effect and mixed-effect predictive models. We will introduce machine-learning approaches for classification and tree-based methods. Results will be interpreted, visualized and discussed. We will introduce the basic elements of data science and analytics using R Project open source software. R is an open-source software project with broad abilities to access machine-readable open-data resources, data cleaning and assembly functions, and a rich selection of statistical packages, used for data analytics, model development, prediction, inference and clustering. For students with little prior R experience, we’ll introduce resources to learn R data types, reading and writing data, looping, plotting and regular expressions. With this background, it becomes possible to start performing variable transformations for linear regression fitting and developing structural equation models, fixed-effects and mixed-effects models along with other statistical learning techniques, while exploring for statistically significant relationships. The class will be structured to have a balance of theory and practice. We’ll split class into Foundation and Practicum  a) Foundation: lectures, presentations, discussion b) Practicum: coding, demonstrations and hands-on data science work. Offered as DSCI 353, DSCI 353M and DSCI 453.

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(Massachusetts Institute of Technology)  
*Kyocera Professor of Ceramics*  
Optical materials science, including optical properties, electronic structure, and radiation durability of optical materials, polymers, ceramics and liquids using vacuum ultraviolet and optical spectroscopies and spectroscopic ellipsometry. Lifetime and degradation science of photovoltaic materials, components and systems including solar radiation durability and degradation mechanisms and rates. Quantum electrodynamics and van der Waals – London dispersion interactions applied to wetting, and long range interactions for manipulation of nanoscale objects such as carbon nanotubes and biomolecular materials.

Peter Lagerlof, PhD  
(Case Western Reserve University)  
*Associate Professor*  
Mechanical properties of ceramics and metals. Of particular interest is to understand how low temperature deformation twinning is related to plastic deformation by dislocation slip at elevated temperatures. Deformation twinning models for both basal and rhombohedral twinning in sapphire, which are properly related to dislocation slip at elevated temperatures, have been established. The basal twinning model has been confirmed experimentally using TEM techniques. Current research involves studies on how to generalize this twinning model to other materials systems; i.e., metals, intermetallic compounds and other ceramics.

John J. Lewandowski, PhD  
(Carnegie Mellon University)  
*Arthur P. Armitage Professor of Engineering; Director, The Advanced Manufacturing and Mechanical Reliability Center (AMMRC)*  
Mechanical behavior of materials; fracture and fatigue; micromechanisms of deformation and fracture; composite materials; bulk metallic glasses and composites; refractory metals; toughening of brittle materials; high-pressure deformation and fracture studies; hydrostatic extrusion; deformation processing.

David H. Matthiesen, PhD  
(Massachusetts Institute of Technology)  
*Associate Professor; Director, Wind Energy Research and Commercialization (WERC) Center*  
Materials for use in wind turbines; wind resource measurements onshore and offshore; materials interactions with ice; bulk crystal growth processing; process engineering in manufacturing; heat, mass, and momentum transport.

James D. McGuffin-Cawley, PhD  
(Case Western Reserve University)  
*Arthur S. Holden Professor of Engineering*  
Powder processing of ceramics; manufacturing and materials; additive manufacturing and rapid prototyping; aggregation phenomena; defects, diffusion, and solid state reactions; materials for optical devices.

Alp Sehirlioglu, PhD  
(University of Illinois at Urbana Champaign)  
*Warren E. Rupp Assistant Professor*  
Energy conversion materials including piezoelectrics and thermoelectrics, high temperature applications, bulk and thin film electro-ceramics, epitaxial oxide thin films.

Gerhard E. Welsch, PhD  
(Case Western Reserve University)  
*Professor*  
Metals and oxides; high temperature properties, mechanical and electrical properties. Materials for capacitive energy storage; metal sponges; high temperature materials, metal-cell composites. Synthesis of materials.

Matthew A. Willard, PhD  
(Carnegie Mellon University)  
*Associate Professor; Director, Case Metals Casting Laboratory*  
Magnetic materials, including their magnetic properties, microstructure evolution, phase formation, and processing conditions; critical materials and sustainability, especially reducing dependence on rare earths through novel alloy design; rapid solidification processing of materials, with an emphasis on nanostructured and amorphous alloys; soft magnetic materials for power conditioning, conversion, and generation technologies and permanent magnet materials for motor, generator, and actuator applications (especially in energy dense applications and in extreme environments); other magnetic related phenomena, including magnetic shape memory alloys, magnetocaloric effects, magnetic nanoparticles, and multiferoics.

**Research Faculty**

Laura S. Bruckman, PhD  
(University of South Carolina)  
*Assistant Professor*  
Electronic materials, lifetime and degradation science, data science.

**Adjunct Faculty**

Arnon Chait, PhD  
(The Ohio State University)  
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ANALIZA, Inc.

George Fisher, PhD  
*Adjunct Professor*  
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(Newcastle University)  
*Adjunct Professor*  
Luxfer Gas Cylinders, Riverside, CA

Jennie S. Hwang, PhD  
(Case Western Reserve University)  
*Adjunct Professor*  
H-Technologies Group, Cleveland, OH

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*Adjunct Assistant Professor*
Terence Mitchell, PhD  
(University of Cambridge)  
*Adjunct Professor*  
Los Alamos National Laboratory, Los Alamos, NM

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Rudolph Podgornik, PhD  
(University of Ljubljana)  
*Adjunct Professor*

Gary Ruff, PhD  
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*Adjunct Professor*  
Ruff Associates, Rochester Hills, MI

Ali Sayir, PhD  
(Case Western Reserve University)  
*Adjunct Professor*  
Air Force Office of Scientific Research

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**Secondary Faculty**

Burda Clemens, PhD  
*Professor of Chemistry*

Liming Dai, PhD  
*Kent Hale Smith Professor*

Walter Lambrecht, PhD  
*Professor of Physics*

Mohan Sankaran, PhD  
*Professor in Chemical Engineering*

Nicole F. Steinmetz, PhD  
*Assistant Professor of Biomedical Engineering*

Russell Wang, DDS  
*Associate Professor of Dentistry*

Xiong (Bill) Yu, PhD, PE  
*Assistant Professor of Civil Engineering*