Additive Manufacturing

Program Description

The Additive Manufacturing program provides graduates and professional students with the practical, interdisciplinary skills to apply cutting-edge additive manufacturing techniques to a wide range of industries, including aerospace, biomedical, defense, and energy, among others.

This program highlights the core foundations of additive manufacturing: process, design, and materials. Students can choose to from a wide range of electives across a variety of categories including data science and machine learning, operational efficiency of manufacturing operations, and entrepreneurship and technology management. The program focuses on additive manufacturing of structural materials and provides users with the skills they need to apply additive manufacturing in modern manufacturing environments.

Contact

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Master of Science in Additive Manufacturing (Non-Thesis) (30 credits)

The Master of Science in Additive Manufacturing (non-thesis) provides students the opportunity to explore a wide range of manufacturing technologies and methodologies necessary to fabricate engineered products in current and emerging markets.

The core courses in the Additive Manufacturing program give students a foundation in additive manufacturing along with options to explore topics across various fabrication and manufacturing efficiency areas. Students enrolled in the Master of Science in Additive Manufacturing (non-thesis) program will complete 9 credits of core courses listed below along with 21 credits of elective courses from the Additive Manufacturing list. The elective list is broken into focus areas to aid students interested in a specific area of additive manufacturing. Students are not required to select a focus area but can choose electives across the entire list.

AMFG501	ADDITIVE MANUFACTURING	3.0
AMFG521	DESIGN FOR ADDITIVE MANUFACTURING	3.0
AMFG531	MATERIALS FOR ADDITIVE MANUFACTURING	3.0
ELECTIVES	Select electives from the Additive Manufacturing list below Up to 6 hours may be replaced with project-based independent study	21.0
Total Semester Hrs		**30.0**

Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

Additive Manufacturing Electives

Note that, while the listed electives are grouped into focus areas, students are not required to select a specific focus area for their degree.

Materials Manufacturing Focus Area		
MEGN511	FATIGUE AND FRACTURE	3.0
MEGN515	COMPUTATIONAL MECHANICS	3.0
MTGN531	THERMODYNAMICS OF METALLURGICAL AND MATERIALS PROCESSING	3.0
MTGN536	OPTIMIZATION AND CONTROL OF METALLURGICAL SYSTEMS	3.0
MTGN557	SOLIDIFICATION	3.0
MTGN560	ANALYSIS OF METALLURGICAL FAILURES	3.0
MTGN564	ADVANCED FORGING AND FORMING	3.0
MTGN565	MECHANICAL PROPERTIES OF CERAMICS AND COMPOSITES	3.0
ELECT	Electives As Approved By Advisor	
Design Manufacturing Focus Area		
AMFG592	ADDITIVE MANUFACTURING BUILD PREPARATION	1.0
FEGN525	ADVANCED FEA THEORY & PRACTICE	3.0
FEGN526	STATIC AND DYNAMIC APPLICATIONS IN FEA	3.0
FEGN527	NONLINEAR APPLICATIONS IN FEA	3.0
FEGN528	FEA FOR ADVANCED DESIGN APPLICATIONS	3.0
ELECT	Electives As Approved By Advisor	
Manufacturing Controls and Data Science Focus Area		
AMFG511	DATA DRIVEN ADVANCED MANUFACTURING	3.0
CSCI507	INTRODUCTION TO COMPUTER VISION	3.0
CSCI534	ROBOT PLANNING AND MANIPULATION	3.0
CSCI562	APPLIED ALGORITHMS AND DATA STRUCTURES	3.0
CSCI575	ADVANCED MACHINE LEARNING	3.0
CSCI587	CYBER PHYSICAL SYSTEMS SECURITY	3.0
DSCI/MATH530	STATISTICAL METHODS I	3.0
EENG509	SPARSE SIGNAL PROCESSING	3.0
EENG515	MATHEMATICAL METHODS FOR SIGNALS AND SYSTEMS	3.0
EENG517	THEORY AND DESIGN OF ADVANCED CONTROL SYSTEMS	3.0
MATH551	COMPUTATIONAL LINEAR ALGEBRA	3.0
MEGN540	MECHATRONICS	3.0
MEGN544	ROBOT MECHANICS: KINEMATICS, DYNAMICS, AND CONTROL	3.0
MEGN545	ADVANCED ROBOT CONTROL	3.0
MEGN587	NONLINEAR OPTIMIZATION	3.0
MEGN588	INTEGER OPTIMIZATION	3.0
ELECT	Electives As Approved By Advisor	
Manufacturing Optimization and Business Focus Area		
AMFG522	LEAN MANUFACTURING	3.0
AMFG523	DESIGN AND ANALYSIS OF EXPERIMENTS	3.0
MEGN579	OPTIMIZATION MODELS IN MANUFACTURING	3.0

CEEN501	LIFE CYCLE ASSESSMENT	3.0
EBGN559	SUPPLY CHAIN ANALYTICS	3.0
EBGN563	MANAGEMENT OF TECHNOLOGY AND INNOVATION	3.0
EBGN576	MANAGING AND MARKETING NEW PRODUCT DEVELOPMENTS	3.0
MEGN592	RISK AND RELIABILITY ENGINEERING ANALYSIS AND DESIGN	3.0

Graduate Certificate in Additive Manufacturing (12 credits)

The graduate certificate in Additive Manufacturing provides students the knowledge and skills needed to design, fabricate, and implement engineered components made using additive manufacturing techniques.

The graduate certificate in Additive Manufacturing is offered fully online to accommodate working professionals outside the immediate geographic area. These courses are also available as elective courses in the current Advanced Manufacturing Masters (non-thesis) and graduate certificate in Smart Manufacturing.

The core courses in the Additive Manufacturing program explore the process, design, and material aspects of additive manufacturing. Students enrolled in the graduate certificate program will complete the three core courses found below along with an elective course from the Additive Manufacturing list.

AMFG501	ADDITIVE MANUFACTURING	3.0
AMFG521	DESIGN FOR ADDITIVE MANUFACTURING	3.0
AMFG531	MATERIALS FOR ADDITIVE MANUFACTURING	3.0
ELECTIVE	Select elective from the Additive Manufacturing list above	3.0

Courses

AMFG501. ADDITIVE MANUFACTURING. 3.0 Semester Hrs.
This course gives students a broad understanding of additive manufacturing (AM) techniques (popularly known as 3d printing) and how these techniques are applied to make engineered products. The course covers the seven standard classifications of AM processes and compares and contrasts each technique alongside legacy fabrication methods such as milling. Students will also get a high-level view of design, material, and pre/post-processing requirements for AM produced parts along with a fundamental understanding of the cost drivers that make AM competitive over legacy fabrication methods. Prerequisites: MEGN200 and MEGN201 or equivalent project classes.
Course Learning Outcomes

- Compare the fundamental differences (speed, accuracy, and cost) between additive manufacturing and subtractive manufacturing.
- Articulate the additive manufacturing process #ow from conceptualization to #nal part.
- Describe the key aspects of each of the seven classi#cations of additive manufacturing technology.
- Compare available post processing methods and select the method(s) that will achieve the desired part characteristics.
- Identify the key di#erences between materials made via additive manufacturing and materials made through conventional fabrication methods in terms of properties, performance, and quali#cation approach.
- Perform a detailed engineering economic analysis to determine if additive manufacturing is the appropriate fabrication method for a given part requirement.
- Utilize design for additive strategies to re-design a conventionally manufactured component assembly and build a prototype of the design using an appropriate additive manufacturing technique.

AMFG511. DATA DRIVEN ADVANCED MANUFACTURING. 3.0 Semester Hrs.
(I) Although focused on materials manufacturing, this course is intended for all students interested in experimental design and data informatics. It will include both directed assignments to reinforce the concepts and algorithms discussed in class and a term project that will encourage students to apply these concepts to a problem of their choosing. Some programming background would be beneficial but is not necessary; the basics of python and the sklearn machine learning toolkit will be covered in the first weeks of the course. 3 hours lecture; 3 semester hours.
Course Learning Outcomes

- 1. Plan and execute design of experiment using, for example Latin Hypercube, Græco-Latin Hypercube, and sequential learning accelerated design of experiment. (Experimental Design.)
- 2. Develop and utilize best practices for high fidelity data collection and curation. (Data Collection and Preprocessing.)
- 3. Extract actionable information from that data through the evaluation and application of appropriate models. (Data Analysis.)
- 4. Effectively communicate to others the impact of these models and how these models guide and optimize a materials manufacturing process. (Data Visualization.)

AMFG521. DESIGN FOR ADDITIVE MANUFACTURING. 3.0 Semester Hrs.
(II) Design for Additive Manufacturing (DAM) introduces common considerations that must be addressed to successfully design or re-design parts for additive manufacturing methods. Industry-leading hardware and FEA software will be used to explore all phases of the DAM workflow, including topology optimization, additive process simulation, distortion compensation, and in-service performance. 3 hours lecture; 3 semester hours.
Course Learning Outcomes

- 1. Execute a topology optimization, interpret results, and re-parameterize geometry to facilitate downstream shape/design refinement.
- 2. Explain the key factors driving support placement in an AM part.
- 3. Use software tools to plan the tool path for an AM process.
- 4. Set part orientation in an AM process to minimize surface area or volume of support material.
- 5. Simulate the thermal history of a part manufactured using an AM process.
- 6. Simulate post-production heat treatment for an AM process.
- 7. Optimize part orientation in a powder-bed AM process to minimize part distortion or maximize in-service fatigue life.
- 8. Clearly communicate in writing the findings of an AM design verification evaluation.

AMFG522. LEAN MANUFACTURING. 3.0 Semester Hrs.
Throughout the course, students will learn to apply skillsets to real world problems, focusing on lean and six-sigma principles and methodologies. The course is taught with a focus on the DMAIC structure of implementation (define, measure, analyze, improve and control) for

improving and implementing process efficiencies in industry. The course is split into three general subject areas; 1) lean manufacturing principles, 2) six-sigma and statistical process control (SPC) methodologies and 3) implementation techniques focusing on graphical and numerical representation of processes using R. Students will receive an in-depth overview of lean manufacturing principles and will perform case studies at local industries to implement learned skill-sets. Next, students will step-through several hands-on activities using real products to investigate six-sigma and perform SPC analysis, identifying shifts in process data and learning how to shift processes into capable processes. Lastly, students will learn about various implementation techniques for industry and will perform an in-depth analysis of the course topics based on the industry tours performed.

Course Learning Outcomes

- • Critique real-time manufacturing processes with regards to information flow, product flow and process times.
- • Identify value adding steps in manufacturing processes in order to better understand where waste lies
- • Recognize real-time wastes in manufacturing processes and facilities and reorganize processes using efficiency models and learned skill-sets to reduce defects found throughout the process
- • Implement lean and six-sigma methodologies to eliminate waste and decrease defects from observed and analyzed processes
- • Utilize R and MiniTab software to create control charts
- • Recognize when to use various applied statistical graphical and numerical representation to understand a process
- • Create analytic reports discussing change implementation plans based on real-time data for upper level management to implement for process efficiency
- • Apply learned skillsets to real-time manufacturing processes and facilities

AMFG523. DESIGN AND ANALYSIS OF EXPERIMENTS. 3.0 Semester Hrs.

This course introduces effective experimental design and analysis methodologies relevant to all engineering and scientific disciplines to maximize the information learned from every experiment (test case) while minimizing the total number of tests. We will be using state-of-art methods steeped in statistics to effectively set up your experiments, understand what the results are telling you, and clearly communicate the results to peers and leadership. We apply a disciplined systems engineering approach across the four major experimental phases: plan, design, execute, and analyze. This hands-on class will focus on understanding concepts and practical applications while relying less on the statistical theoretical development. Completion of MATH201 is recommended, not required.

Course Learning Outcomes

- At the completion of this course, students will: 1) Formulate an analytically defensible test strategy using foundational principles across the Plan-Design-Execute-Analyze phases of experimentation.
- 2) Apply statistically-based methods to understand results and quantify risk from single factor experiments.
- 3) Create and analyze full-factorial test designs with multiple input explanatory variables understanding the critical importance of interactions.
- 4) Construct appropriate test designs to screen many possible input factors to isolate those few variables that drive system behavior.
- 5) Construct response surface test designs that build on screening methods to characterize nonlinear behavior often seen in practical applications.
- 6) Compare alternative experimental designs with statistically-based performance metrics.
- 7) Assess advanced experimental designs that better fit the actual test environment rather than forcing the problem to conform into a common design.

AMFG531. MATERIALS FOR ADDITIVE MANUFACTURING. 3.0 Semester Hrs.

(II) This course will cover various structural materials used in additive manufacturing (AM) processes. Focus will be on polymer, ceramic, and metallic compositions. General chemistry of each material will be covered with additional focus on the behavior of these materials when processed using AM. The course will span the entire AM lifecycle from feedstock fabrication to fabrication by AM to post processing and inspection of as-fabricated material. Students will have hands-on exposure to AM processes and will conduct laboratory studies of AM material properties. Additionally, students will conduct a semester-long research project exploring some aspect of AM materials. 3 hours lecture; 3 semester hours.

Course Learning Outcomes

- 1. List the polymer, ceramic, and metallic materials most commonly used in AM processes
- 2. Describe the key features necessary in a material (polymer, ceramic, metal) that make it amenable to AM processes
- 3. Describe the differences between AM processed materials and conventionally processed materials
- 4. Describe the manufacturing processes used to create feedstock materials
- 5. List common defects in AM materials and explain how they form and how they can be avoided
- 6. Describe the common post processing methods for various AM materials and explain why they are necessary and/or useful

AMFG581. OPTIMIZATION MODELS IN MANUFACTURING. 3.0 Semester Hrs.

This course explores the process of taking known inputs such as costs, supplies and demands, and determining values for unknown quantities (variables) so as to maximize or minimize some goal (objective function) while satisfying a variety of restrictions (constraints). Such problems arise in manufacturing operations as personnel planning, product sequencing, and plant scheduling. We examine a variety of manufacturing settings, e.g., flow shops, job shops, flexible manufacturing shops, and the corresponding appropriate models to optimize operations. The course explores a mix of mathematical modeling, software use and case studies. Prerequisite: Junior standing in an engineering major, or instructor consent.

Course Learning Outcomes

- Understand the concepts of optimization as applied in a manufacturing setting. See syllabus.

AMFG591. ECONOMIC CONSIDERATIONS FOR ADDITIVE MANUFACTURING. 1.0 Semester Hr.

This course will provide students an opportunity to explore the economic considerations for advanced manufacturing processes, specifically additive manufacturing (AM). So often, these processes are thought of as being quick, easy, and cheap. While this can be true for prototypes and

other non-critical parts, the reality is much different when working with engineered parts. An examination of the underlying engineering details for AM processes reveals many elements of cost and time which must be accounted for when evaluating the affordability of AM for any application. Students will learn about recurring and non-recurring costs, the reasons for post-processing steps such as machining, mechanical testing, and non-destructive inspection, and the impacts of these considerations on cost and manufacturing span-time. Students should expect to come away from this course better equipped to assess the economic viability of AM for engineering applications.
Course Learning Outcomes

- Economic Analysis
- Requirement Differentiation
- Process Formulation
- Additive Manufacturing Cost Estimation

AMFG592. ADDITIVE MANUFACTURING BUILD PREPARATION. 1.0 Semester Hr.
This course covers practical aspects of additive manufacturing build preparation, which include designing a part, part build orientation, and support structures. It distinguishes these concepts from those of traditional manufacturing methods and addresses how they influence final part outcome in regard to mechanical performance, dimensional accuracy, surface finish, and post processing requirements. Similarities and differences in these concepts are covered as they apply to various additive manufacturing technologies. These concepts are integrated to ultimately provide students with the ability to holistically approach design for additive manufacturing. Prerequisite: AMFG401 or AMFG501.
Course Learning Outcomes

- At the completion of this course, students will: 1) Use CAD software to design and export parts to buildable file formats.
- 2) Use CAD software to apply color, design, and texture to part surfaces.
- 3) Apply concepts of additive manufacturing to design a part or assembly.
- 4) Apply concepts of additive manufacturing to determine part build orientation.
- 5) Apply concepts of additive manufacturing to design support structures.
- 6) Integrate concepts of part design, orientation, and support structures to apply a holistic design strategy to additive manufacturing.
- 7) Differentiate additive manufacturing technologies as functions of their design considerations.

AMFG598. SPECIAL TOPICS IN ADVANCED MANUFACTURING. 1-6 Semester Hr.
(I, II) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once. Prerequisite: none. Variable credit; 1 to 6 credit hours. Repeatable for credit under different titles.

AMFG598. SPECIAL TOPICS IN ADVANCED MANUFACTURING. 1-6 Semester Hr.

AMFG599. INDEPENDENT STUDY. 1-6 Semester Hr.

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Director and Professor of Practice

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