Design for Additive Manufacturing

A Training Course

Course Overview

This course is intended to be a technical elective course for Mechanical and Manufacturing Engineering. This non-classic course aids students to develop a new set of skills and mindset which is different than the conventional ways of thinking about design. The current design process has been conceived within the constraints of a world where advanced AM (Additive Manufacturing) did not yet exist. This course will be on the philosophy and practice of the design style that makes best use of the features and capabilities of AM, without neglecting that a big fraction of the concepts within traditional design still hold true. It reviews the rules, methods, software and tools to assist a designer in understanding the design freedom allowed by AM and aiding the designer in exploring the open design spaces with less or no constraints. After completing this course, students learn new techniques to design for manufacturability using AM, plus learn the process and part characterization in AM.

After an introductory review of various AM technologies, including: Stereolithography, Laser sintering, Fused deposition modeling, etc., discussion on efficiency of AM from a strategic and operational point of views, and AM attributes in terms of cost, rate, flexibility and quality, the heart of this course consists of seven Modules: (i) AM materials processes and applications (ii) Implicit modeling, (iii) Topology optimization, (iv) Design for lattice structures, (v) Part consolidation, (vi) Design support, and (vii) Process, Part characterization, and Quality assessment of a printed part.

Module 1 explains the engineering aspects and physical principles of available AM technologies and their applications. It reviews the recent developments in this technology and the criteria needed to successfully select an AM technology for a particular design, discussing material compatibility, interfaces issues and strength requirements. In Module 2 students learn the concept of implicit modeling which is different than regular CAD feature-based (faces, edges, lines, points, curves, and surfaces) modeling approaches. They build their knowledge of implicit modeling concept through applying it in other modules. They implement it through using a commercial software *(nTop)*. In Module 3 students learn, Topology optimization, a technique which can optimize material layout within a given design space. In Module 4. Students learn how to take advantage of the unique capabilities of AM processes which provide a great design freedom for designers to use light weight cellular/lattice structures. Students learn how to apply this technique in design of light weigh structures or complex internal passages for heat exchangers on fluid distribution systems. They become also familiar with various applications of AM in human implant made of lattice structure which can enhance osseointegration in the biomedical field. Most CAD system cannot deal with lattice structures where you have thousands or millions features. To help students to take use of AM capabilities, students apply the concept of implicit modeling which they become familiar in Module 1 here. Module 5 involves redesigning an object such that it has fewer parts with substantially different boundaries and connections. So, it may no longer need to be an assembly at all. In traditional manufacturing methods, some complex components are usually separated into several parts for the ease of manufacturing, and then are assembled together. But complex part can be fabricated by AM in one shot. This module helps students to learn how to take use of this advantage. Module 6 teaches students how to design a part which has overhang and requires support when it is manufactured by AM. Module 7 reviews part characterization in AM. It involves methods to evaluate a metal printed part in terms of its strength, hardness, toughness, and fatigue life. In this module they learn different techniques to check the physical and mechanical properties of a printed part.

During these six modules, students will become familiar with some applications of these techniques through some industrial case studies. They also will learn current trends and techniques of Metal 3D printing, such as Powder Bed Fusion, Direct Metal Deposition by Welding, and Paste Deposition Modeling. They also become familiar with the sintering process. They will learn different technique for creating STL and Slicing of a part to optimize for a Metal 3D printer.

Students will master these topics through completing a capstone project, in which they design and manufacture a complex part, using a Metal 3D printer. The course capstone project, involves forming a team (3 or 4 students), proposing a part, and justify why it cannot be made by the traditional manufacturing processes, design and model the part, make the part (printing and sintering), and test its quality. Through this journey students gain perspective on the advantages and disadvantages of AM and the future of Design and Manufacturing. They would also gain insight on the four attributes of AM, cost, rate, quality, and flexibility in comparison with other manufacturing processes.

Course vector

4 Credit [3-2-0], Lectures (Two 1.5-hours), Lab (One 2-hours)

Course description for calendar

Design for Additive Manufacturing, Implicit Modeling, Topology Optimization, Design Light Weight Structures, Lattice Structure, Process, Part characterization, and Quality assessment of a printed part

Instructor: Ahmad Mohammadpanah **Contact**: mpanah@mail.ubc.ca	Date/Time

Pre-Requisite: Mech 392 or MANU 380
Co-Requisite: Mech 462 or equivalent or background in FEA

Required Textbook:

Some chapters from the following three books will be used. Additional chapters from other textbook, plus additional notes and papers will be recommended to students as well.

- **Design for Additive Manufacturing, Martin Leary, 2019**

This book provides a basic guide to design tools for the manufacturing requirements of AM and how they can enable the optimization of process and product parameters for the reduction of manufacturing costs and effort. Some chapters of the book will be a good discussion source on metallic and polymeric AM technologies and their manufacturing attributes. The book will be a good resource for students to study the commercial applications of AM with case studies from a range of industries. It demonstrates the best-practice in AM design, including some case studies that showcase best-practice in AM design, including the biomedical, aerospace, defense and automotive sectors.

- **Additive Manufacturing, Andreas Gebhardt, 2016**

This book presents the basics of additive manufacturing and the properties and special aspects of industrially available machines. The book will be a good resource to review various AM technologies, including: Stereolithography, Laser sintering, Fused deposition modeling. There is a useful chapter on the efficiency of AM from a strategic and operational point of views.

- **Additive Manufacturing of Metals, John O. Milewski, 2017**

This book will serve as a reading source on introduction to AM of metals. It provides many examples ranging from rocket nozzles to custom jewelry to medical implants which illustrate a new world of freedom in design and fabrication, creating objects otherwise not possible by conventional means. A chapter of this book which describes the various methods and advanced metals, and how harnessing the power of lasers, electron beams, and electric arcs, as directed by advanced computer models, robots, and 3D printing systems, is used to introduce different metal printing technologies.

Required Software:

- nTop
- Fusion 360

Equipment/Lab:

- Metal 3D Printer and Sintering (available at Mech)
- Computer lab (*e.g.* Pace Lab)

Course Format

The course will be delivered through lectures supported by application examples. *nTop* as the leading software in Implicit Modeling (equations and field driven) and *Fusion 360* for Explicit modeling (regular geometrical features) will be the main two software in this course. Students design and make a part as their final project, using the available metal printer. This course will be delivered in seven main Modules with combination of lecture-based, computer-based, and hands-on sessions.

After an introductory review of various AM technologies, including: Stereolithography, Laser sintering, Fused deposition modeling, etc., discussion on efficiency of AM from a strategic and operational point of views, AM attributes in terms of cost, rate, flexibility and quality, and introducing some commercial applications of AM with case studies from a range of industries, including the biomedical, aerospace, defense and automotive sectors. the heart of this course consists of six Modules:

Module I. AM materials processes and applications

This module serves as an introduction which explains the engineering aspects and physical principles of available AM technologies and their applications. It reviews the recent developments in this technology and the criteria needed to successfully select an AM technology for a particular design, discussing material compatibility, interfaces issues and strength requirements.

Module II. Implicit Modeling

While tremendous design potential with AM technologies waiting for designers to explore, there is one big caveat. They need good CAD modeling approaches to support their exploration. Current CAD techniques are less than ideal for taking advantage of the unique capabilities of AM in creating novel shapes and structures. For example, geometric complexity, which needs to support models with hundreds of thousands of features, faces, curves, and edges, is not possible. Autodesk Fusion 360, ProEngineer, Ideas, Unigraphics, SolidEdge, CATIA, SolidWorks, and many others are very good for representing shapes of most engineered parts. Their feature-based (faces, edges, lines, points, curves, surfaces) modeling approaches enable fast design of a regular parts. These systems have boundary representation of part geometry and topology. A vast amount of information is needed, for providing design interactions, graphics, mass properties, and interfaces to other CAD or FEA and CAE, or the CAM tools.
In this module students learn a new concept in modeling, “Implicit Modeling”. Implicit modeling has many advantages over conventional CAD modeling methods, including the ability to model with any analytic surface models, and its avoidance of complex geometric and topological representations.
Unlike conventional CAD systems (explicit modeling), which parametric curves and surfaces are the primary geometric entities used in modeling, in filed driven (implicit modeling) equations are the primary entities used in modeling. Students will learn the concept and foundation of implicit modeling and they will learn how to use a commercial software *(nTop)* to implement implicit modeling.
This module will be delivered through standard lectures, explaining the concepts terminologies, theories, and techniques. There will be basic assignments (quite mathematical in nature) to practice the newly learned concepts. The lectures will be accompanied by weekly computer-based lab where students apply these techniques through various examples in a software.

Module III: Topology Optimization

Topology optimization is a technique which can optimize material layout within a given design space. It can update both shape and topology of a part. It can help designers to get an optimal complex geometry for AM.
In this module, students explore how the distributions of material can be optimized. They learn how to determine the overall configuration of shape elements in a design problem, then perform FEA during each iteration of the optimization method, until the optimization process results in structures that are nearly fully stressed, or have constant strain energy, throughout the structure geometry based on the specified loading conditions. They become familiar with two main methods: Truss-based and Volume-based density. They will also gain experiences through presenting many actual optimized examples.
This module will be delivered through standard lectures, explaining the concepts, theories, and techniques. A basic knowledge of FEM and FEA is essential to follow along with the practice problems in this module. There will be

some fundamental problems (stress and strain analyses in nature) to practice the newly learned concepts. The lectures will be accompanied by weekly computer-based lab where students apply the topology optimization techniques through various examples.

Module IV: Design for Lattice Structures

The unique capabilities of AM provide a great design freedom for designers to use cellular structures or lattice structures. For example, in the aerospace field, lattice structures fabricated by AM process can be used for weight reduction. In this module, students become familiar with various internal structures, such as TWPS (thin wall periodic structure), Gyroid, Isogrid, Honeycomb, etc. and learn how to use these internal structures in design of light weigh structures or complex internal passages for heat exchangers on fluid distribution systems.

Lattice structures are difficult to manufacture by traditional method. These structures can be found in parts in the aerospace and biomedical industries. But, thanks to AM, making this type of structures are possible. This module also teaches students how to choose an optimum lattice structure, with considerations such as manufacturability, reliability, and cost which are subjected to the capabilities of additive manufacturing technologies.

This module will be delivered through standard lectures, explaining the concepts, theories, and techniques, accompanied by weekly computer-based lab where students learn how to apply this technique in design of different examples, such as light weigh aerospace structures, complex internal passages for heat exchangers on fluid distribution systems, and various applications of AM in human implant made of lattice structure which can enhance osseointegration in the biomedical field.

Module V. Part consolidation

Part consolidation involves redesigning an object such that it has fewer parts with substantially different boundaries and connections. So, it may no longer need to be an assembly at all.

In traditional manufacturing methods, some complex components are usually separated into several parts for the ease of manufacturing, and then are assembled together. But complex part can be fabricated by AM in one step. This module first covers the rules in traditional design for assembly, which their main considerations are often to reduce assembly time, tools, the number of parts and eliminate fasteners. Then through this module, students explore a design process in order to minimize parts and fasteners. They learn that integrated part designs typically become much more complex and expensive or even impossible to manufacture by traditional processes. In fact, this will be the fever pitch of the course, and students learn many factors in design for consolidation which must be considered, such as, the trades off between complex component and the cost of assembly. They will learn how the two main attributes of manufacturing, cost and complexity play a major role on the success of AM verses other processes.

This module will be delivered through a manifold of practical examples. There will be some basic and some demanding practice problems and assignments, so students could practice the concepts.

Module VI. Design techniques for parts which require support

After a part is designed, the STL is created and sliced, so ready for printing, there might be a portion of a part which overhang, as a result, due to gravity the part will deforms. In more extreme cases, it is not possible to deposit a layer, because due to the geometry, there is no first layer to support it. In this case, the designer needs to know how to orient the part to minimize the amount of support. It is also essential to design the support appropriately.

This module will be delivered through standard lectures, in which, students will be exposed to a plethora of examples to understand how to design in order to minimize the need for support and if inevitable, how to design the support and how to calculate if the strength of the support is enough to handle the weight of the overhang portion of a part. They learn the current technologies in AM for adding a support, such as ceramic and evaporative supports. In this module, they develop a great understanding of different AM technologies, such as Powder Bed Fusion, Direct Metal Deposition by Welding, and Paste Deposition Modeling and their pros and cons. For example, they learn if a part should be manufactured with powder bed SLS technique to avoid building an expensive support or maybe Metal deposition is a better choice; and many other examples.

Module VII. Process, Part characterization and Evaluation of a printed part

How good the printed part is compared with a part if made by machining, forging, casting, or powder metallurgy? How can we judge a printed part in terms of Strength, Stiffness, Toughness, Hardness, Durability, Weight, Heat and Electrical Conductivity, Corrosiveness, Appearance and Feeling, Cost of the raw material, Cost of process and maintenance, and Safety issues?

In this module, students learn various techniques to evaluate the Mechanical and Physical properties of a printed part. They become familiar with some basic experimental tests. To thoroughly understand this module, an experimental test is designed. Several simple parts (e.g. a small beam with rectangular cross-section) with similar geometries and materials, made by Metal 3D printing, but with different deposit orientation are made, and some tests may conducted as follow:

The yielding strength, module of elasticity, and fatigue life of these printed beams are compared with same beam from a solid stainless steel made by machining, through simple mechanical tests. A typical Modal analysis of these beams then are conducted, to shows the vibration behavior of them. An AE (Acoustic Emission) test is also conducted to evaluate the porosity of these printed beams and compare with solid beam.

Students will also learn that there are some other parameters besides the deposition orientation, such as the intensity or exposure time of the drying lamp after each layer, the speed of deposition, the nozzle size, the flow speed, etc. which can affect the properties of a printed part. The sintering cycles which also have significant effect on the final part surface hardness and many other mechanical properties are studies. So, the objective of this module is to teach students a systematic way to evaluate the metal printed objects and compare them with the same part if made by machining from a solid billet. The delivery of this module will be lab-based.

Course Objectives

The objective of this course is to develop a new set of skills and mindset which is different than the conventional ways of thinking about design. After completion of this course, students become familiar with new rules, methods, software and tools to design for manufacturability using Additive Manufacturing (AM). They learn how to take advantages of the freedom allowed by AM and aid them in exploring the open design spaces with less or no constraints.
Students will become familiar with some applications of AM through some industrial case studies. They learn current trends and techniques of Metal 3D printing, such as Powder Bed Fusion, Direct Metal Deposition by Welding, and Paste Deposition Modeling. They also become familiar with the sintering process. After completion of this course, they also learn various technique for creating STL and Slicing of a part to optimize for a Metal 3D printer.
Students learn the concept of implicit modeling. They implement it through using a commercial software (nTop). They build their knowledge of using this software through applying the topics they learn in other modules. Students learn Topology optimization, a technique which can optimize material layout within a given design space. They learn various internal structures for designing light weight cellular/lattice structures. They also become familiar on how to use these techniques in different applications such as designing of light weight aerospace structures, complex internal passages for heat exchangers on fluid distribution systems.
Students develop skills in how to redesign an object such that it has fewer parts with substantially different boundaries and connections in order to remove the need to be an assembly. They compare the redesigned part with traditional manufacturing methods, in which, some complex components have to be separated into several parts for the ease of manufacturing, and then are assembled together.
Students analyze the design of parts which requires support during printing, and learn how to design supports to minimize the amount of support materials and time for printing.

They learn tools and methods to evaluate a metal printed part in terms of its Strength, Stiffness, Toughness, Hardness, Durability, Weight, Heat and Electrical Conductivity, Corrosiveness, Appearance and Feeling, Cost of the raw material, Cost of process and maintenance, and Safety issues.
At the end of this course, students gain perspective on the advantages and disadvantages of AM, the current trends and challenges of AM and the future of Design and Manufacturing. They gain insight on the four attributes of AM, cost, rate, quality, and flexibility in comparison with other manufacturing processes.

Learning Outcomes

- Become familiar with current AM technologies, the terminologies, the advantages and disadvantages of AM
- Analyze the AM attributes in terms of Cost, Rate, Flexibility, and Quality
- Understand the concept of "Implicit Modeling".
- Be able to run a software, with implicit modeling capabilities, for modeling a part with complex internal structures
- Be able to design a part considering the design constraints and boundaries (with a view to conventional manufacturing processes) and then optimize material layout within a given design space for topology optimization.
- Be able to justify why a part cannot be manufactured using the traditional manufacturing processes.
- Becomes familiar with various lattice structures
- Become familiar with examples where a designer can take advantages of AM for design of light weight aerospace applications or optimized heat exchangers with internal complex passages.
- Know how to orient a part, design support (if necessary), create STL, generate G-code and slicing, for a part to be ready to be sent to a printer
- Be able to evaluate the trades off between complex component and the cost of assembly.
- Be able to run the Metal 3D printer and the sintering furnace, and produce one functional part.
- Learn how to evaluate the quality of printed part (mechanical and physical properties)
- Gain insight on the four attributes of AM, cost, rate, quality, and flexibility in comparison with other manufacturing processes.
- Gain insight on the future of manufacturing and the application of AM

Evaluation Criteria

The assessment strategy for this course is typical of many engineering courses, as we routinely assess students on the basis of their ability to recall and apply relevant facts and theories, to perform calculations correctly and evaluate their responses for plausibility, to demonstrate competence in design methodologies, and to be able to communicate technical information effectively.

Assignments (conceptual, theoretical, analyses, modeling, and software projects) in this course allow students to practice and apply newly learned techniques. The topics in this course build upon each other, and so material presented early in the term (mainly in Module 1) is critical to the understanding of material presented later in the term (in Module 2 and 3), and later critical for applying them (in Module 4-5). Giving some weight to weekly assignments encourages students to practice the material covered in the course consistently throughout the term, which improves the overall outcome for the students. Students have the ability to work with others and seek help during office hours.
After completing Module 1, 2, and 3 there will be a midterm exam (quiz), which give the students an opportunity to demonstrate their knowledge in a controlled testing environment and may include a combination of calculation-based problems, concept designs, modeling, scrutinizing a design, applying different topology optimization techniques to a certain problem or illustration of knowledge of relevant facts and techniques pertained to AM. The results of the exam, plus the assignments will be used to assess the students' understanding of the fundamental theorems, concepts, and the use of software before moving on to the next module.

The course instructor would be remiss in his duty if he neglects to underscore the fact that learning the concepts in each module in this course is demanding and takes time. One Key in true and lasting knowledge in this course is practicing through modeling and designing various parts and applying various techniques to different parts. Luckily, there are a plethora of industrial and practical examples available for demonstration and practice.

The capstone project in this course, which involves forming a team (3 or 4 students), proposing a part, and justify why it cannot be made by the traditional manufacturing processes, design and model the part, make the part (printing and sintering), and test its quality, will be weighed a large portion of the final grade. This assignment verifies that students have mastered a majority of the material covered in the course, are able to work in a team, write a technical document, and ability to present their work. Grading of the capstone project will be based on both appropriate methods of design, and applying the design for manufacturability with AM techniques. These serve to assess a multiple learning outcome in combination, thus giving the ability to assess the capacity of the students to understand the design for additive manufacturing.

Possible Grading scheme:

- Assignments/Software Projects (different weight for each Module): 30%
- Midterm: 30%
- Capstone project: 40%

Course Schedule *(tentative – a detailed schedule will be developed after course approval)*

Date	Topics
Week 1	Module 1
Week 2	Module 1
Week 3	Module 2
Week 4	Module 2
Week 5	Module 2
Week 6	Module 3
Week 7	Module 3, Midterm
Week 8	Module 4, Course Capstone Project Proposal
Week 9	Module 5, Course Capstone Project Feedback
Week 10	Module 6, Work on Capstone Project
Week 11	Module 6, Work on Capstone Project
Week 12	Examples, Industrial Case studies,
Week 13	Review, Projects showcase, Feedback, …